A method to develop centrifugal compressor performance maps for off-design and dynamic simulation studies of sCO_2 cycles

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Co-authored by Pieter Rousseau & Ryno Laubscher, Stellenbosch University

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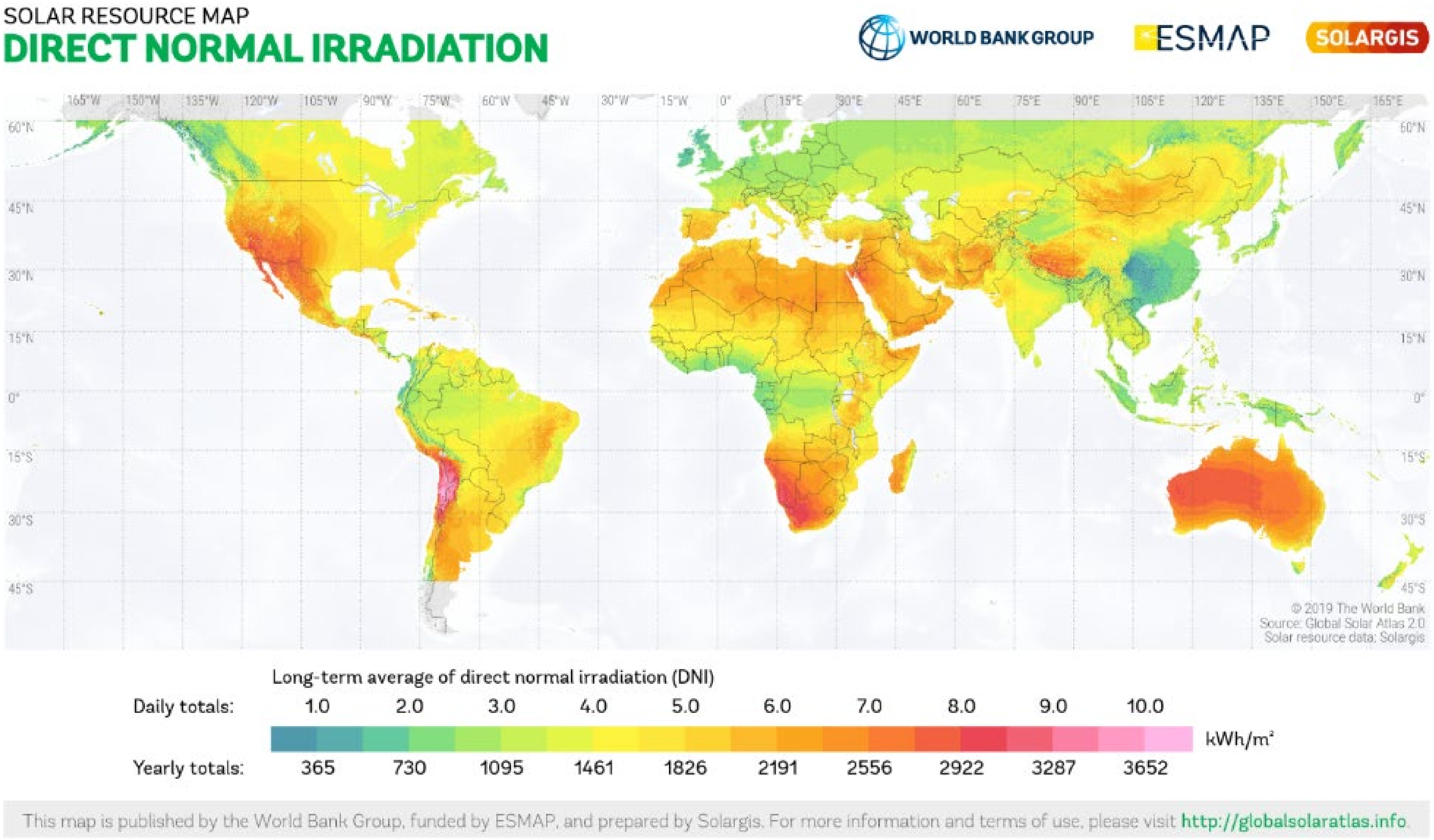

Global direct normal irradiation map, from The World Bank (2019)

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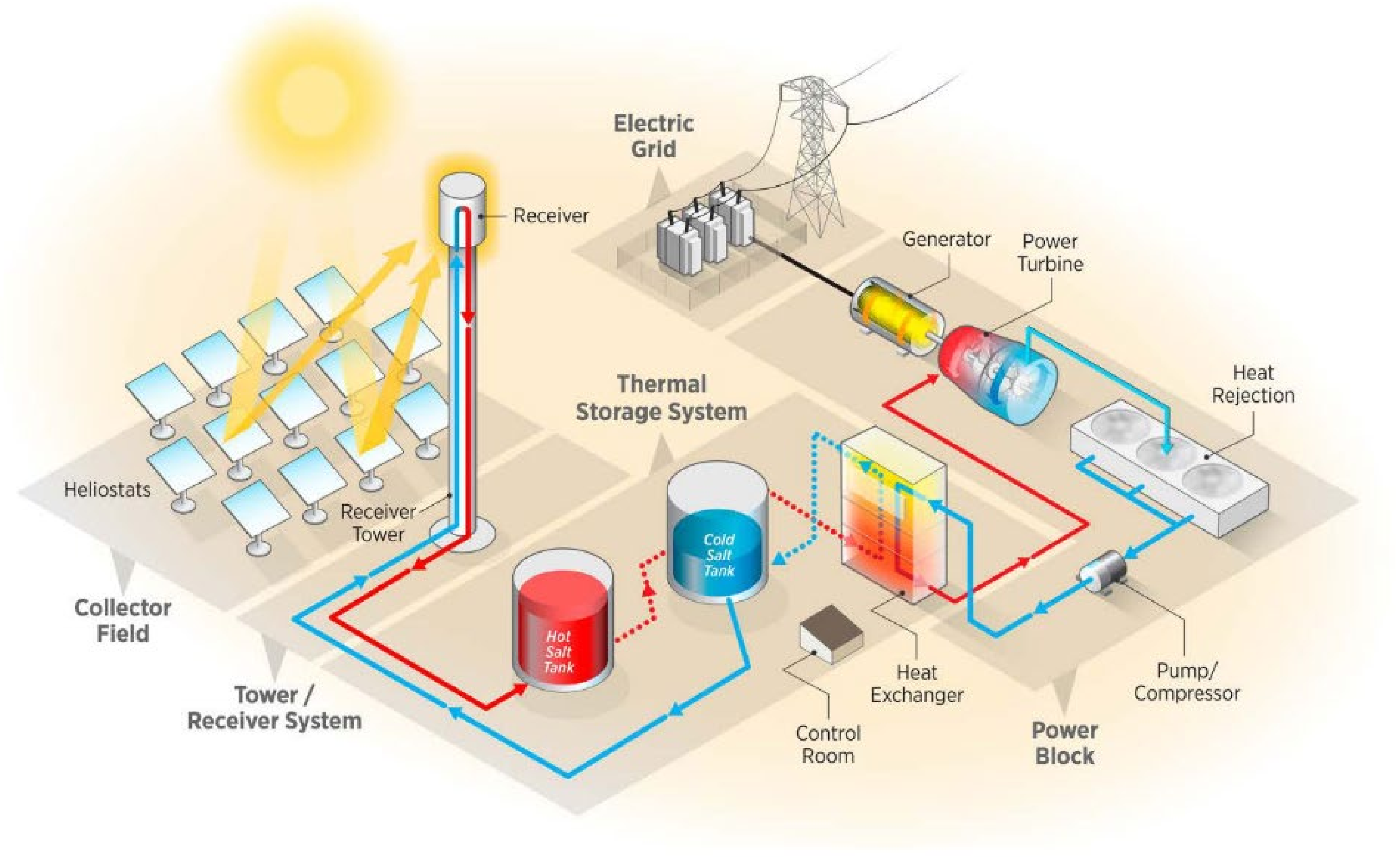
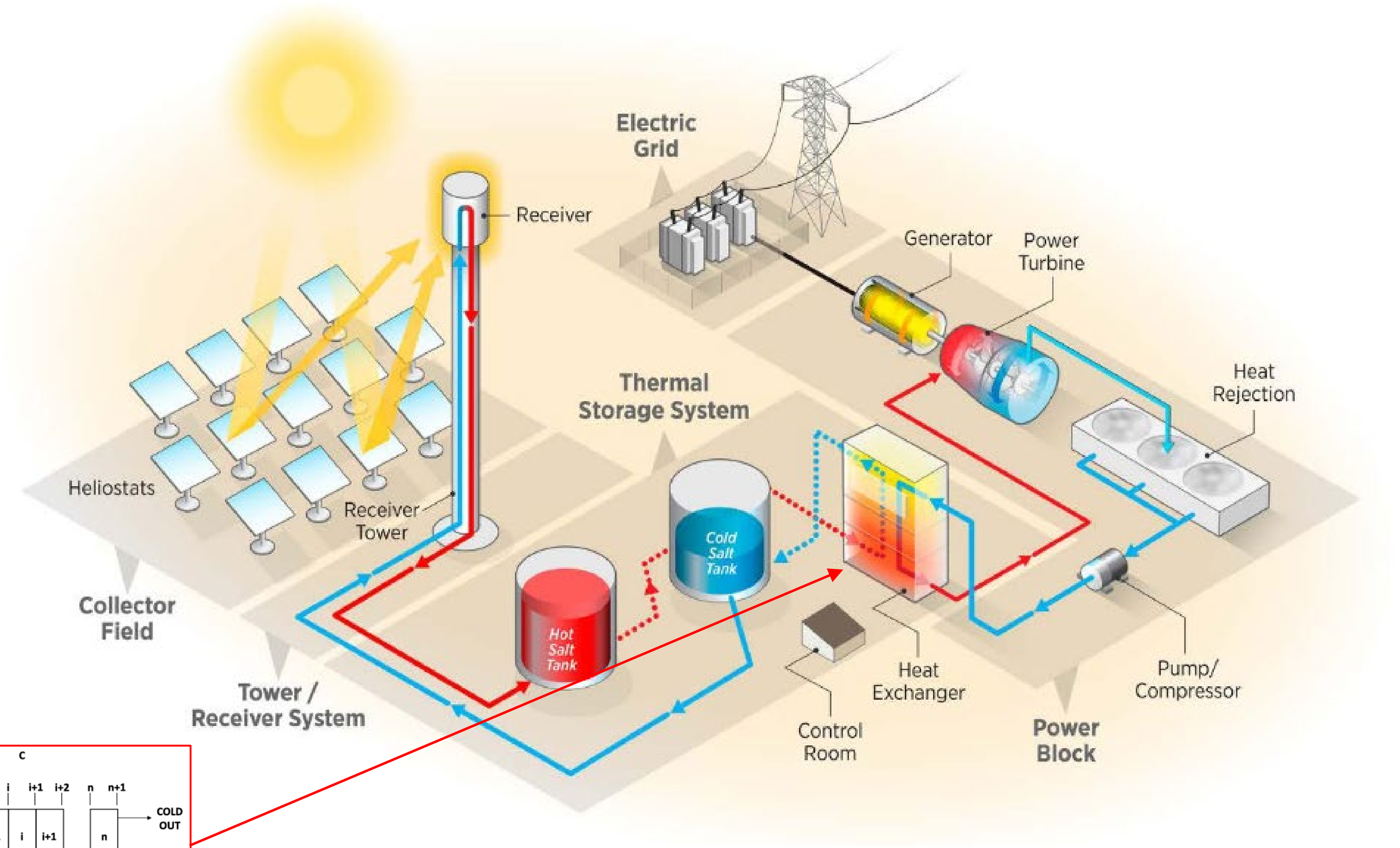
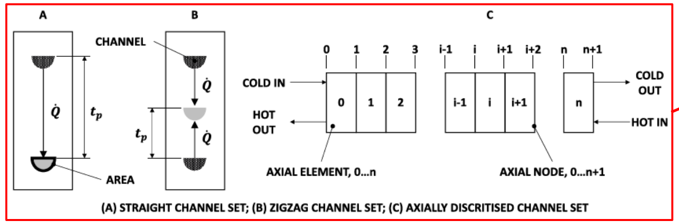


Schematic of a sCO2-CSP plant with TES, from Mehos et al. (2017)

Introduction





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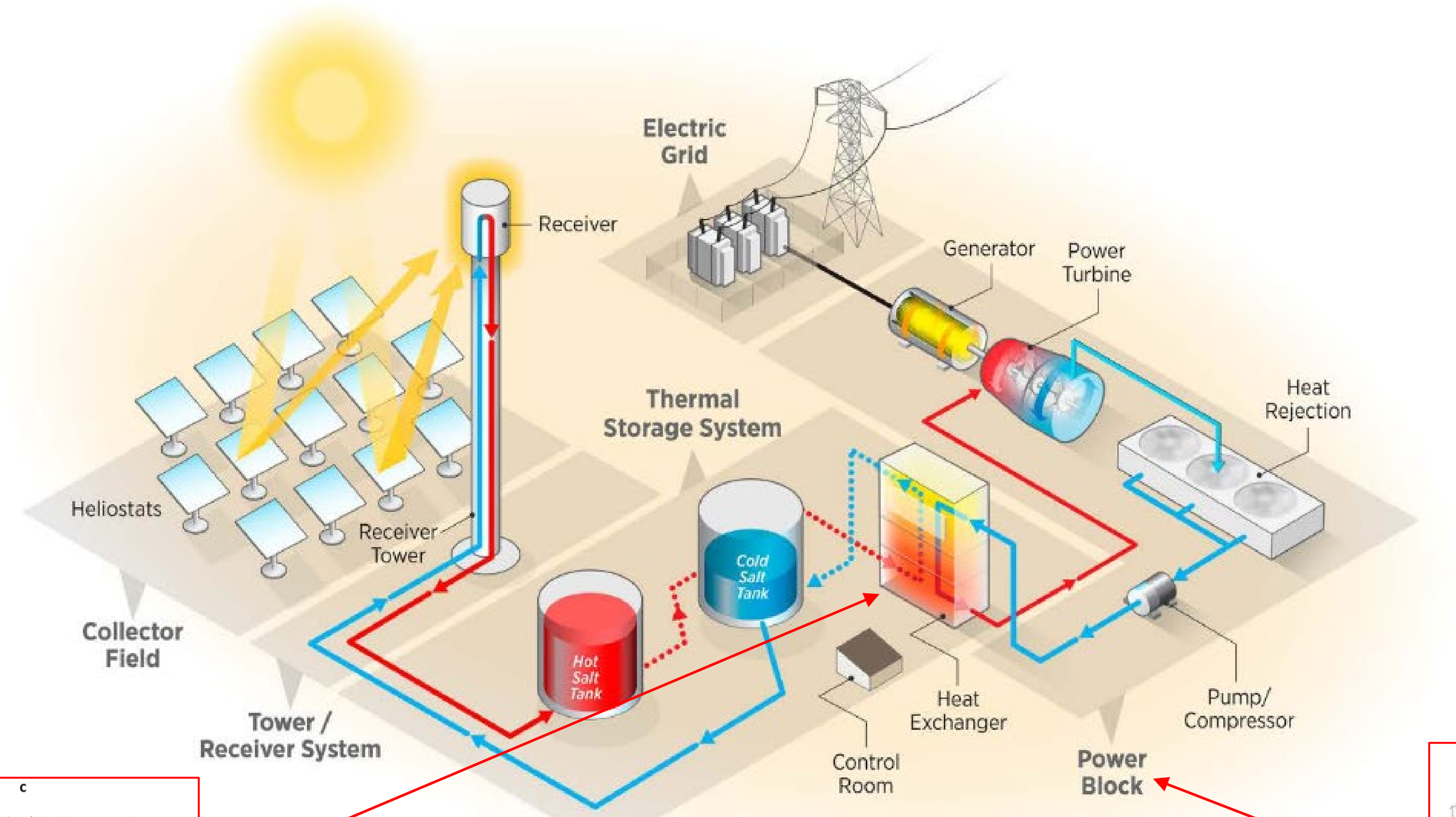

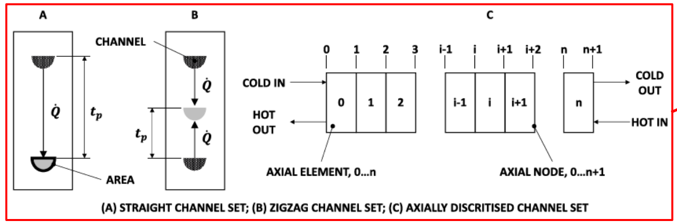

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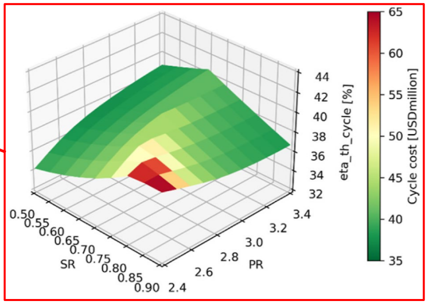

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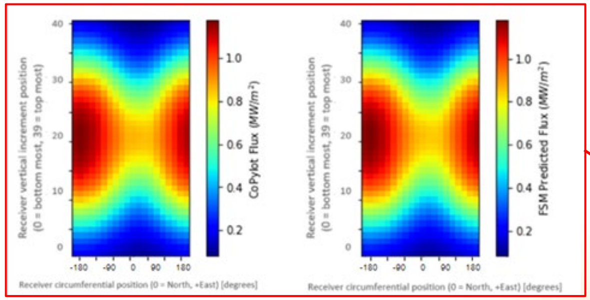

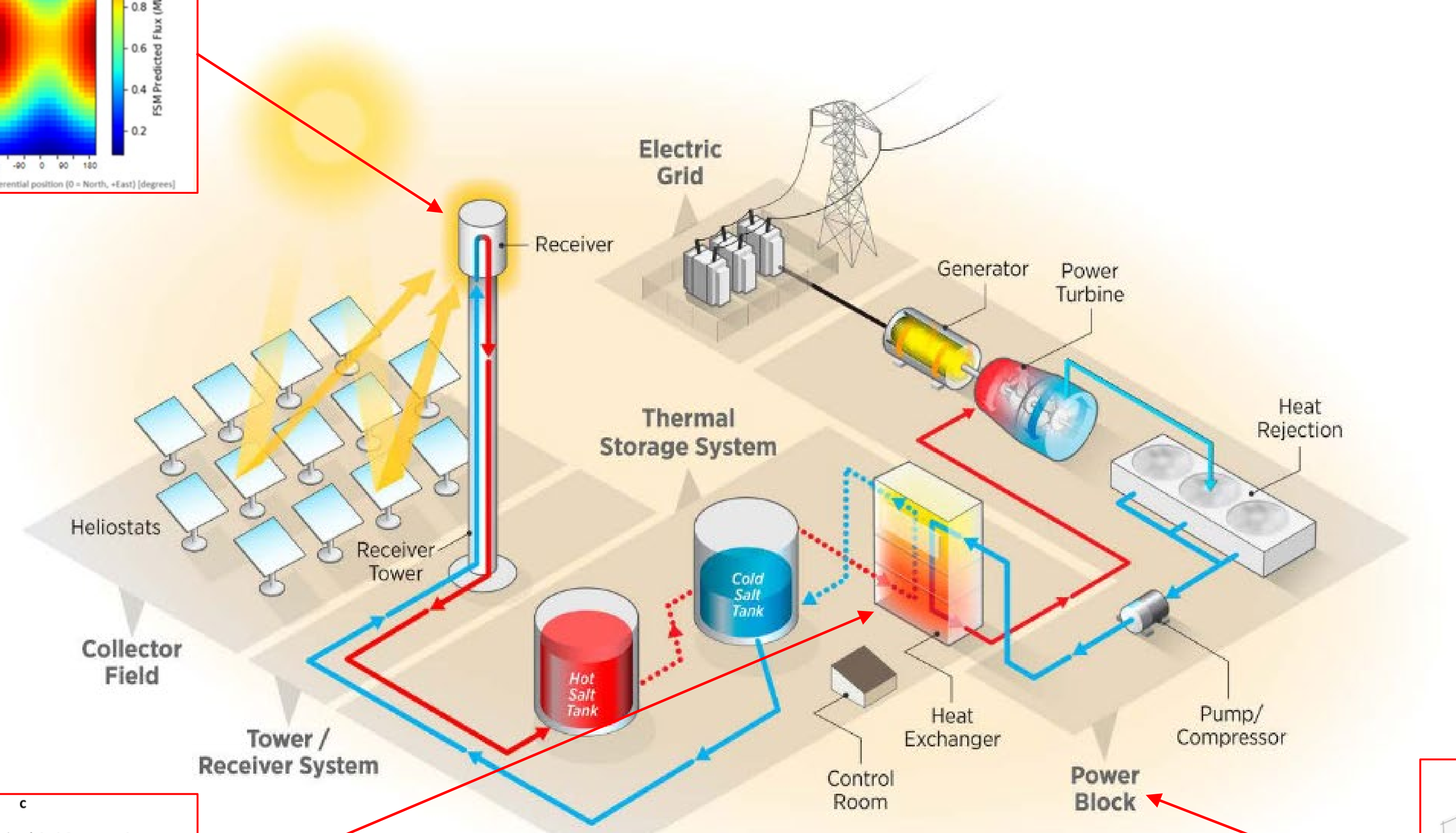

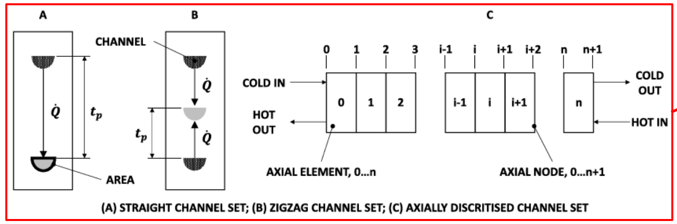

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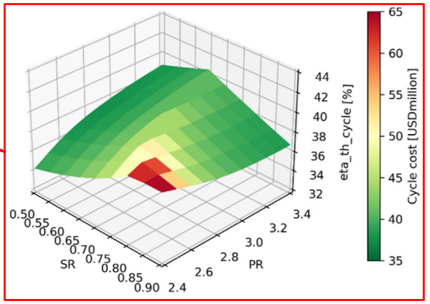

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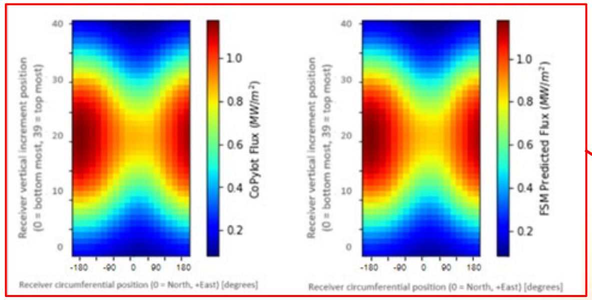

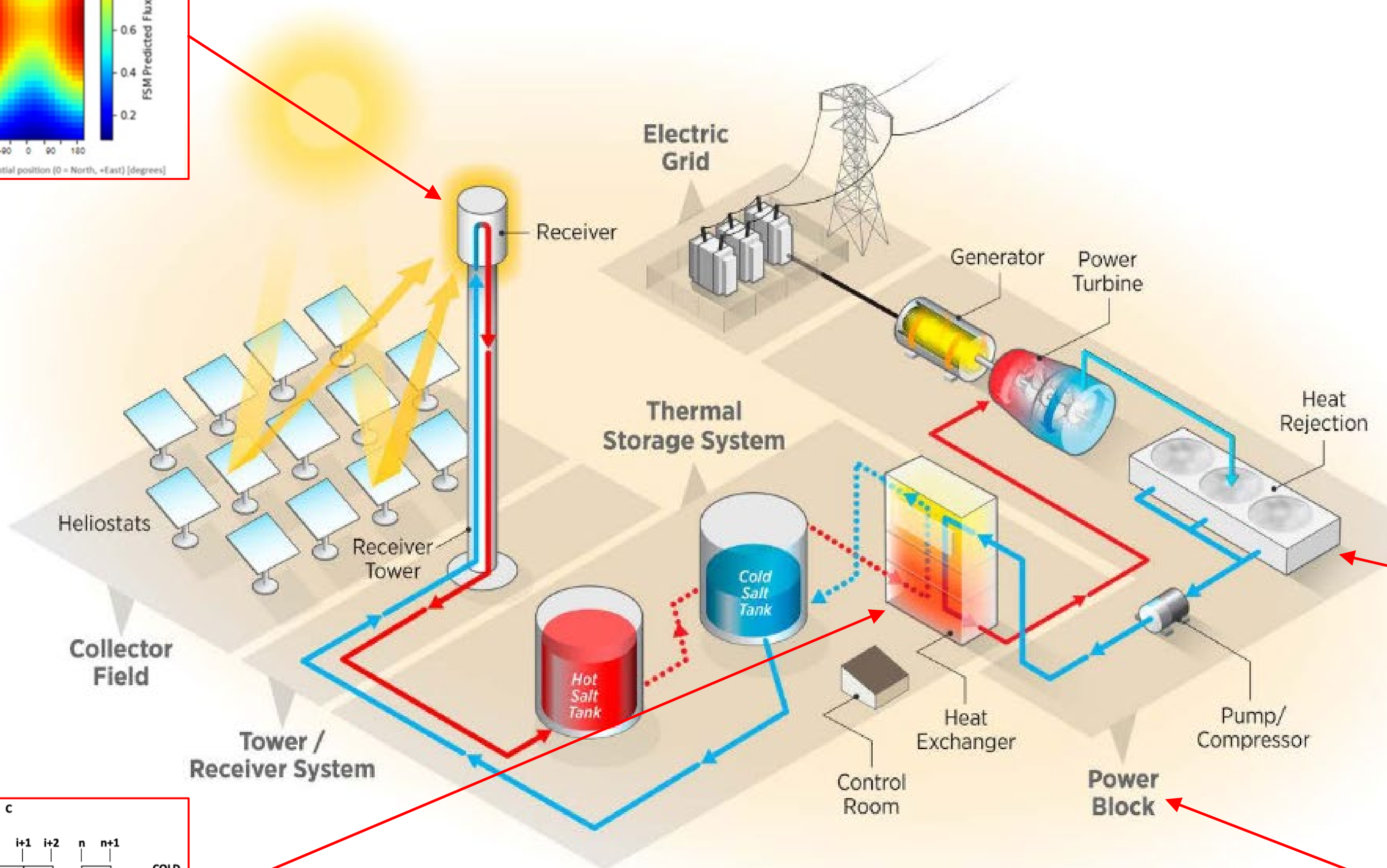

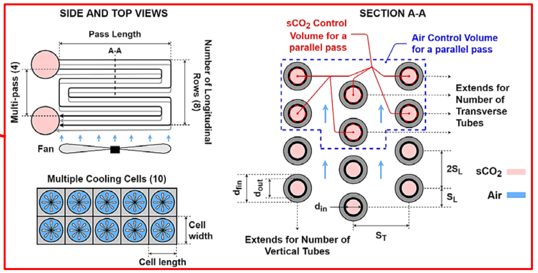

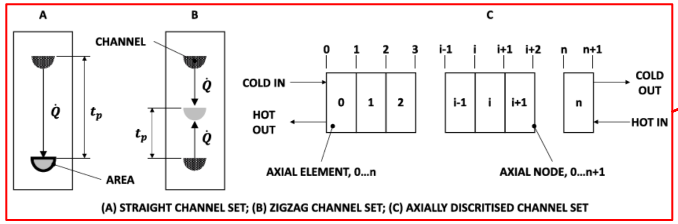

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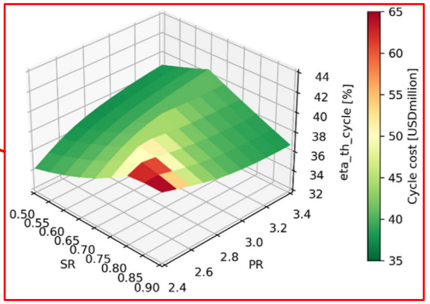

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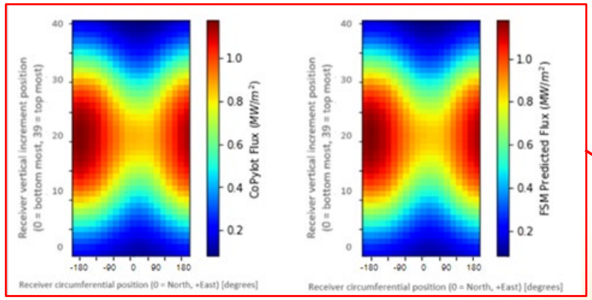

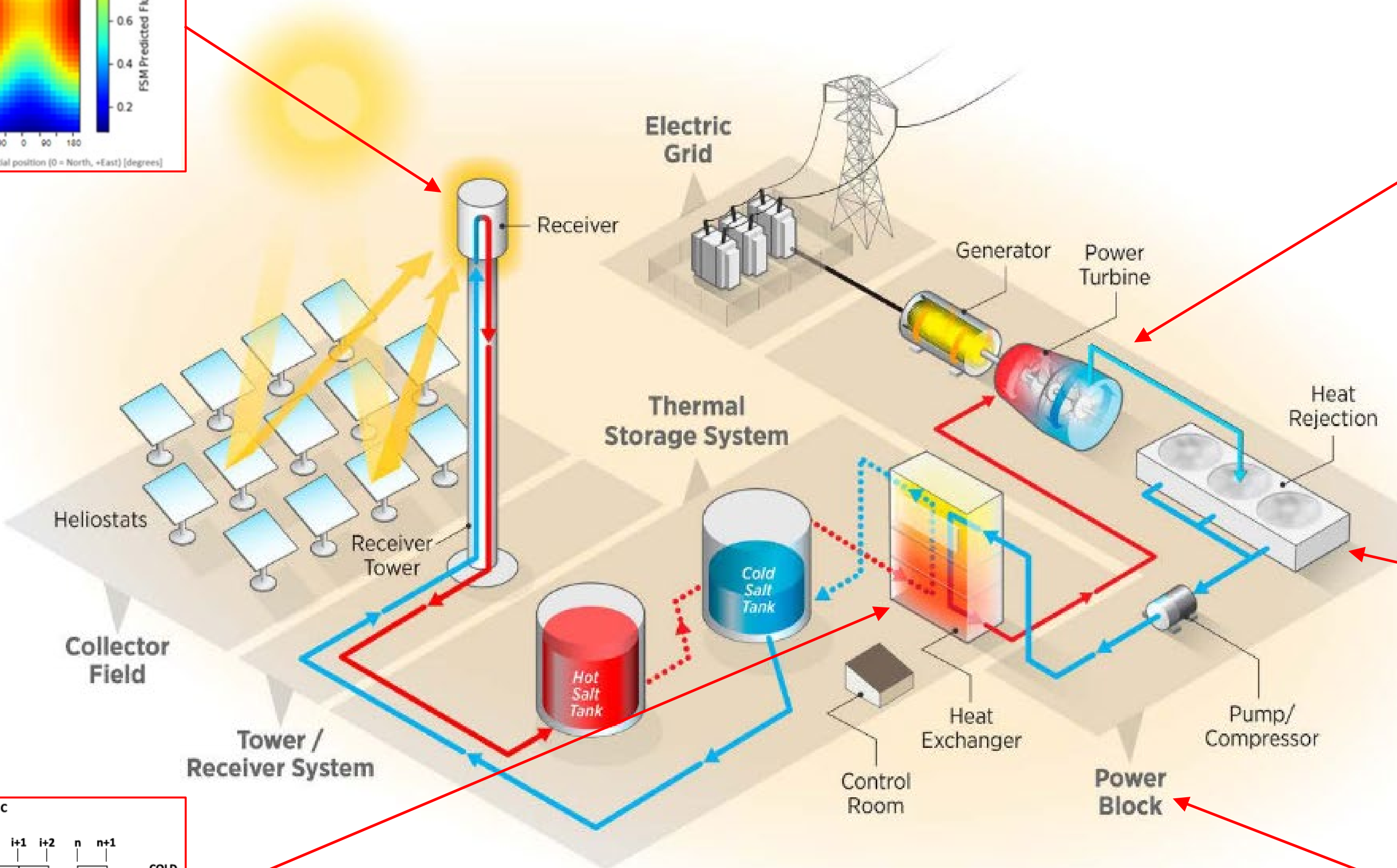

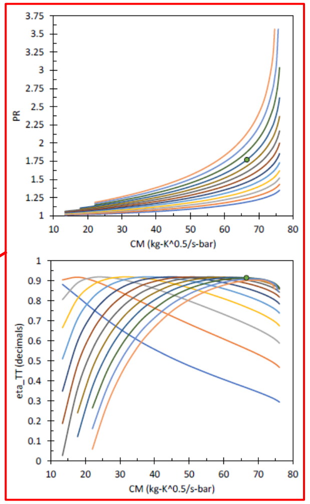

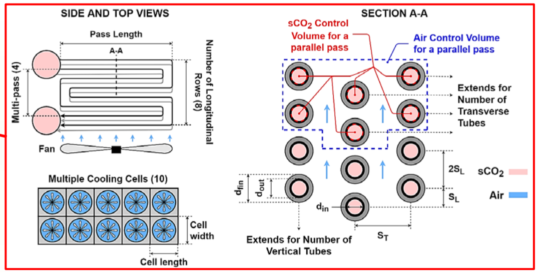

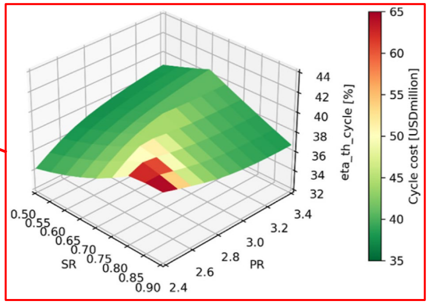

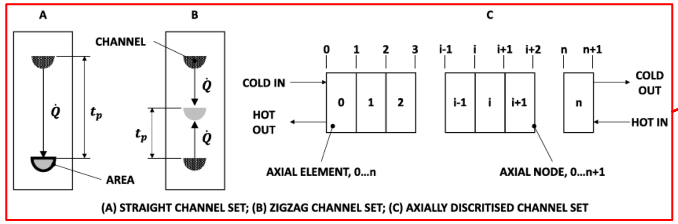

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Study type	Steady-state	x			x	x	x	x	x							x	
	Quasi-steady			x						x	x	x		x	x		x
	Dynamic		x										x				
Turbomachinary models	Isentropic			x	x	x		x	x	x	x	x		x	x		
	Dyreby's method/ curve fit						x						x		x	x	x
	Performance maps by others/ software	x	x														
	Tailor-made design and maps																
	Inertia effects																
Off-design performance, control and simulations	Off-design performance						x										x
	Off-design control	x														x	
	Daily simulation									x		x	x				
	Annual simulation			x							x				x		
	Fast transients		x														

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	Quasi-steady			x						x	x	x		x	x		x
	Dynamic		x										x				
Turbomachinary models	Isentropic			x	x	x		x	x	x	x	x		x	x		
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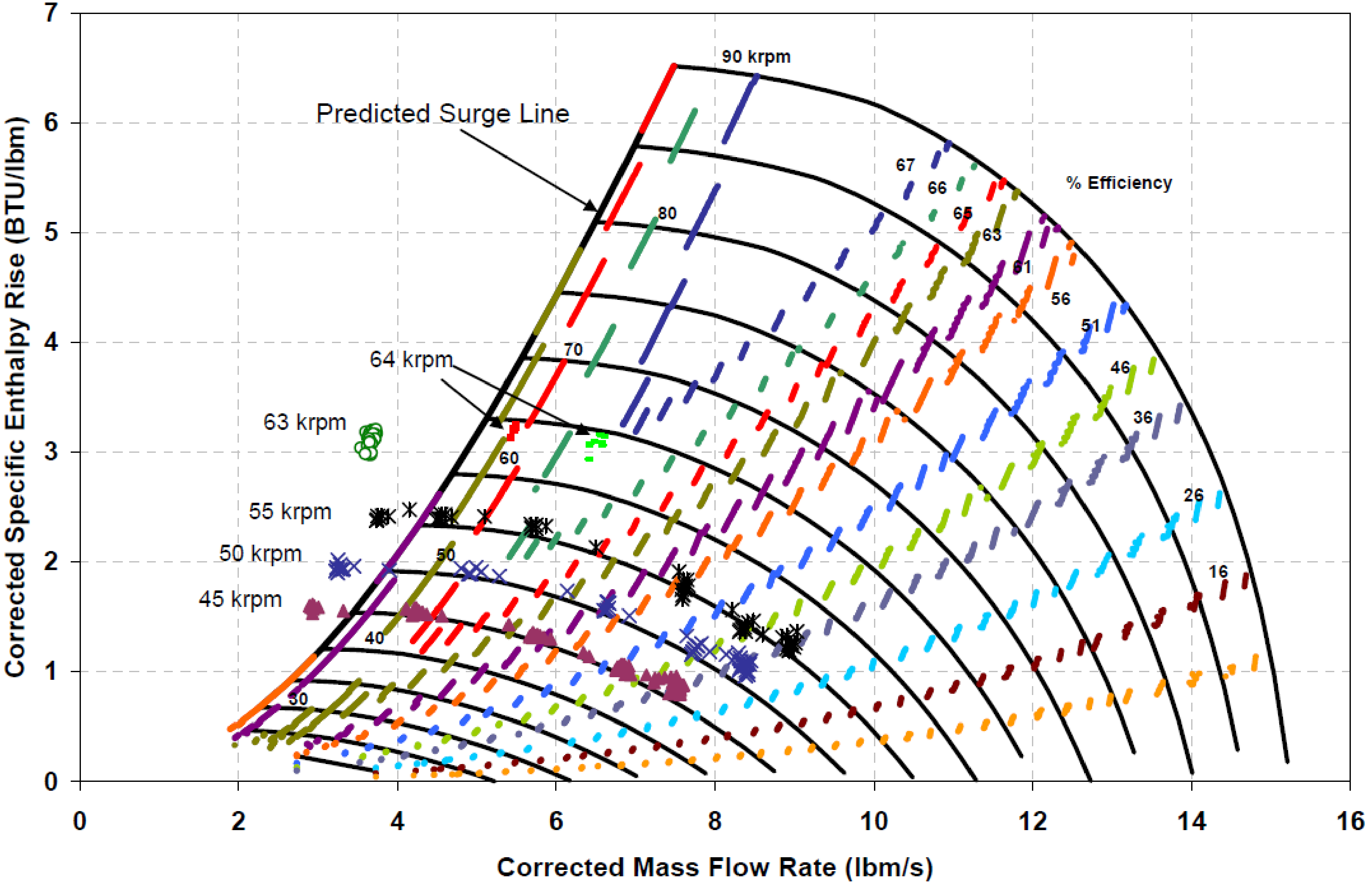
Dyreby's method



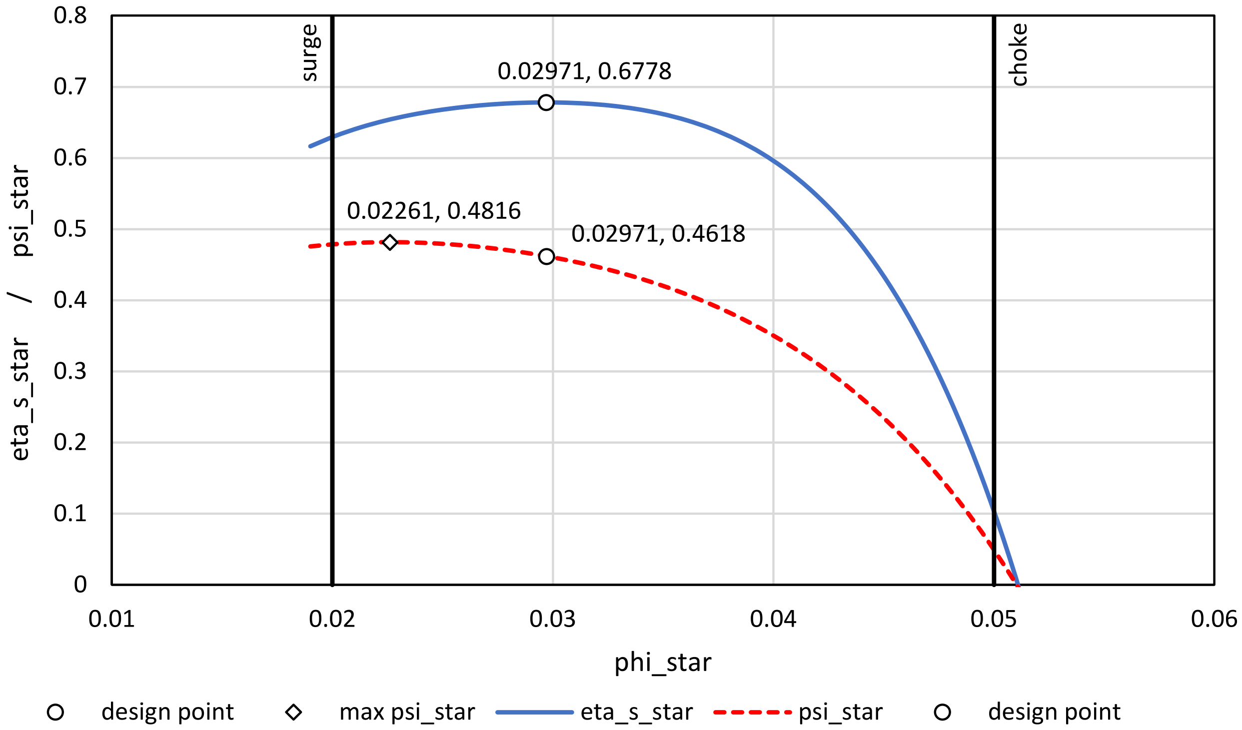
SNL compressor performance map, from Wright et al. (2010)

Dyreby's method

$$\eta^* = -0.7069 + 168.6\phi^* - 8089\phi^{*2} + 182725\phi^{*3} - 1.638e^6\phi^{*4}$$

$$\psi^* = 0.04049 + 54.7\phi^* - 2505\phi^{*2} + 53224\phi^{*3} - 498626\phi^{*4}$$

$$\phi^* = \phi\left(\frac{N}{N_{nom}}\right)^{0.2} = \frac{\dot{m}}{\rho_1 u_2 D_2^2}\left(\frac{N}{N_{nom}}\right)^{0.2} \qquad \eta^* = \eta\left(\frac{N_{nom}}{N}\right)^{(20\phi^*)^5} \qquad \psi^* = \psi\left(\frac{N_{nom}}{N}\right)^{(20\phi^*)^3} = \frac{w_{c.s}}{u_2^2}\left(\frac{N_{nom}}{N}\right)^{(20\phi^*)^3}$$



Head and efficiency correlations, from Dyreby (2014)

1D mean-line codes

KAIST-TMD:

- Private 1D mean-line based tool to size centrifugal compressors and generate performance maps.
- Developed by Lee (2016) for the design of sCO_2 centrifugal compressors.
- Used by collaborators i.e., Cho et al. (2019) and Jeong et al (2020) for compressor-focused studies.

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AlFa CCD:

- Private 1D mean-line based tool to size centrifugal compressors and generate performance maps.
- Developed by Ameli et al (2018) for the design of ~~sCO_2~~ centrifugal compressors.

1D mean-line codes

Compared to this work:

- Fewer compressor components considered.
- Models not fully documented.
- Different correlation sets applied.
- Verification results leave room for improvement.

1D mean-line codes

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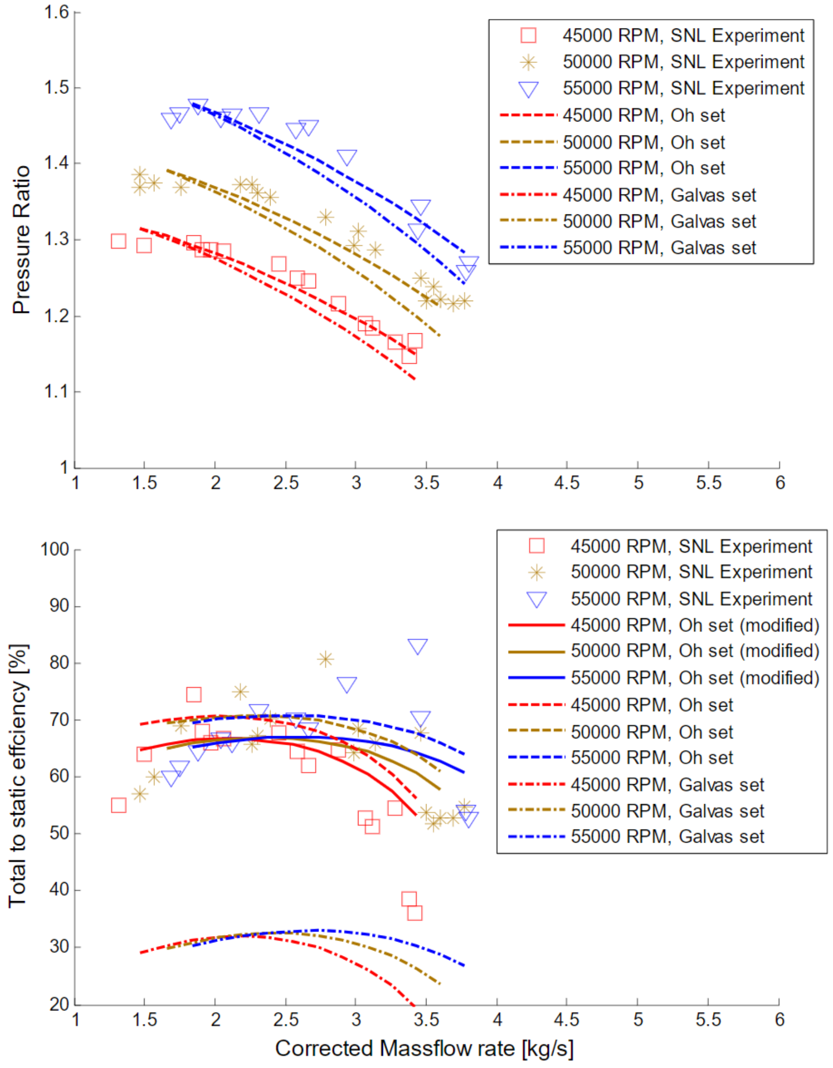
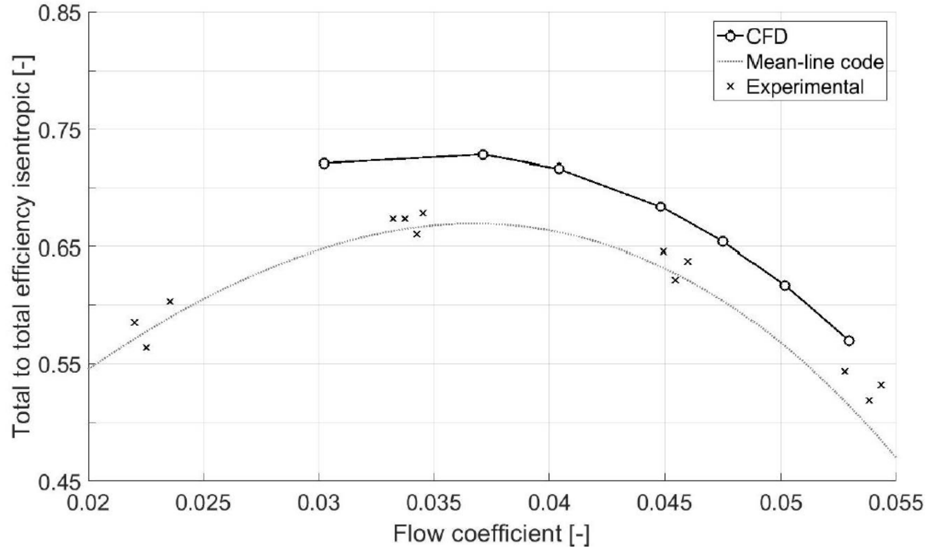
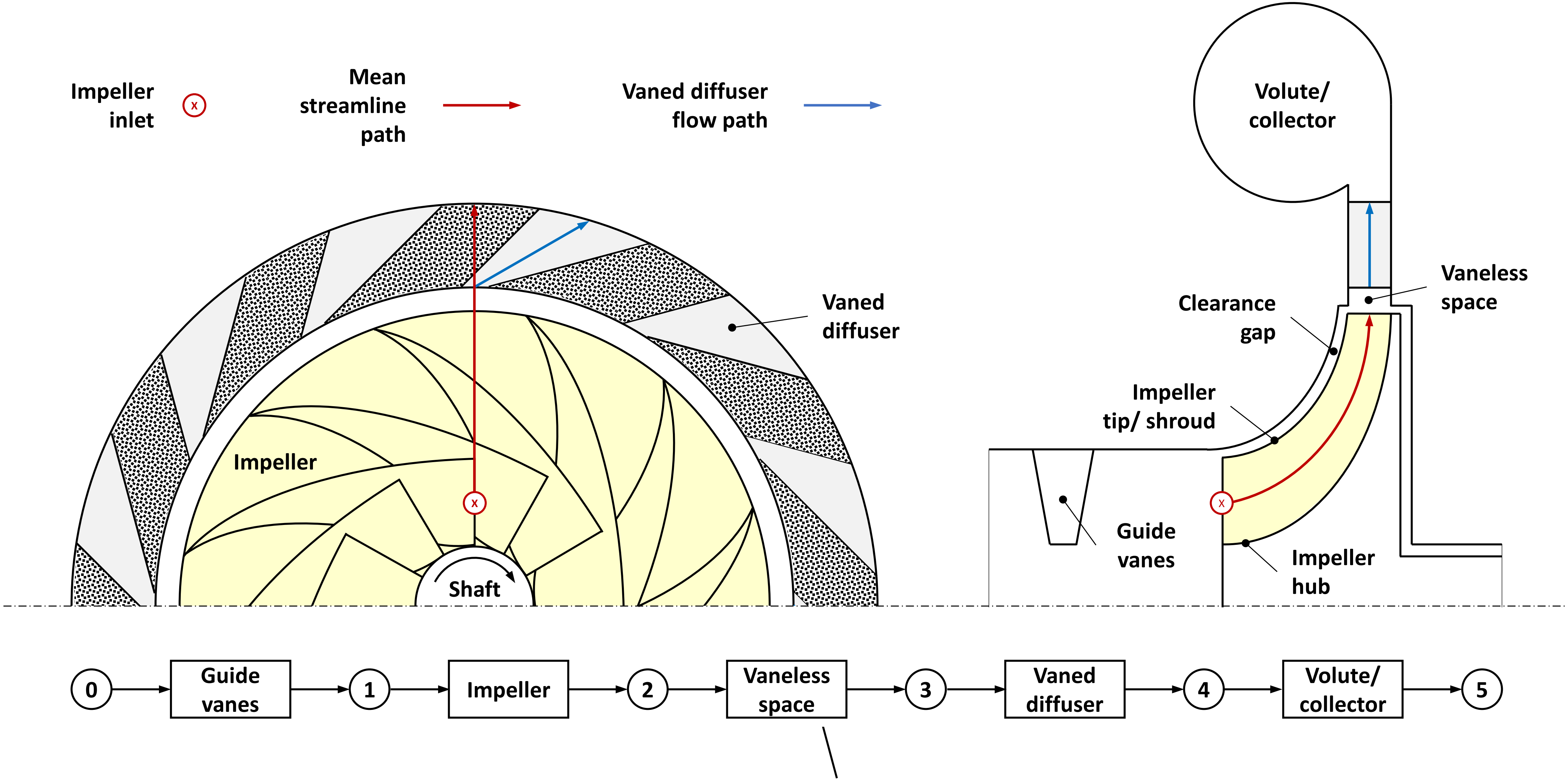


Verification results, from Lee (2016)

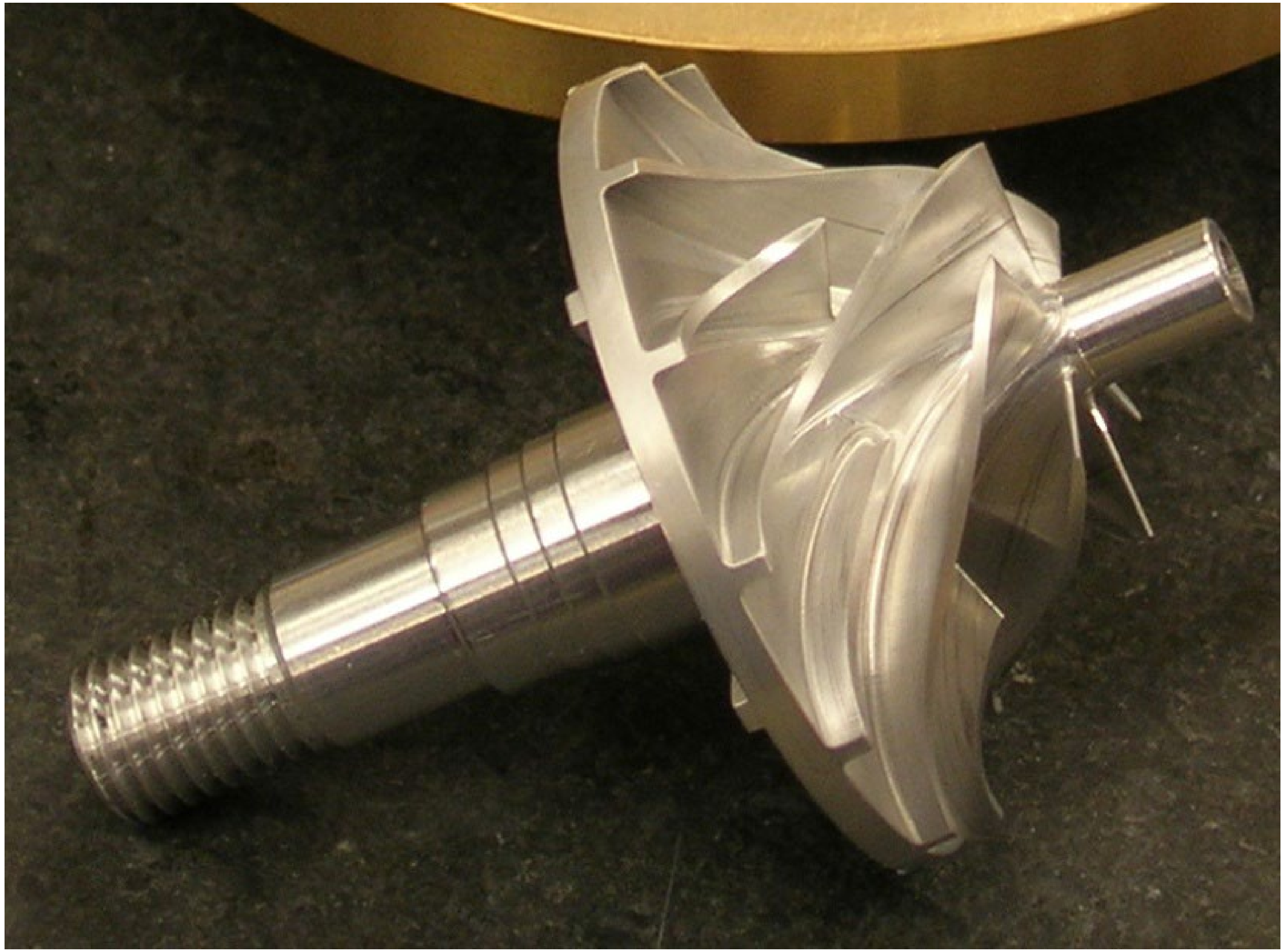


Verification results, from Ameli et al. (2018)

Model development



Model verification

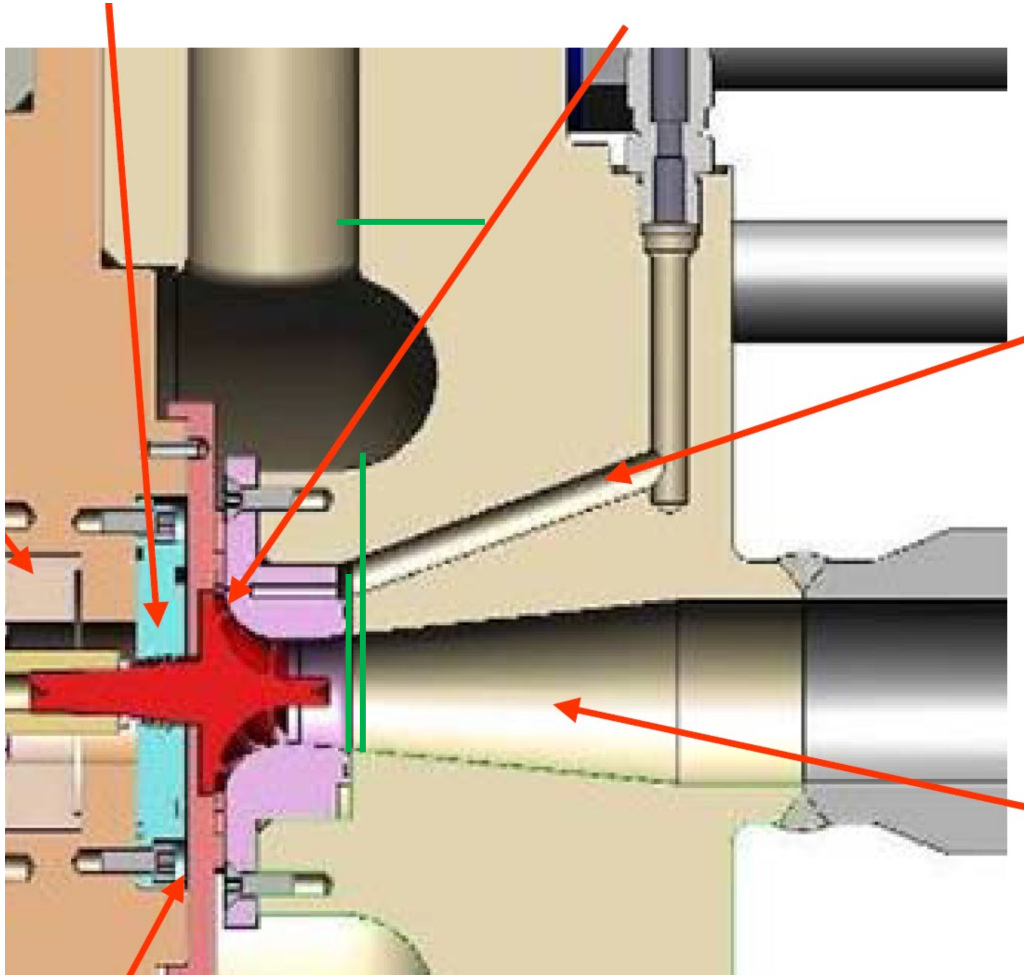


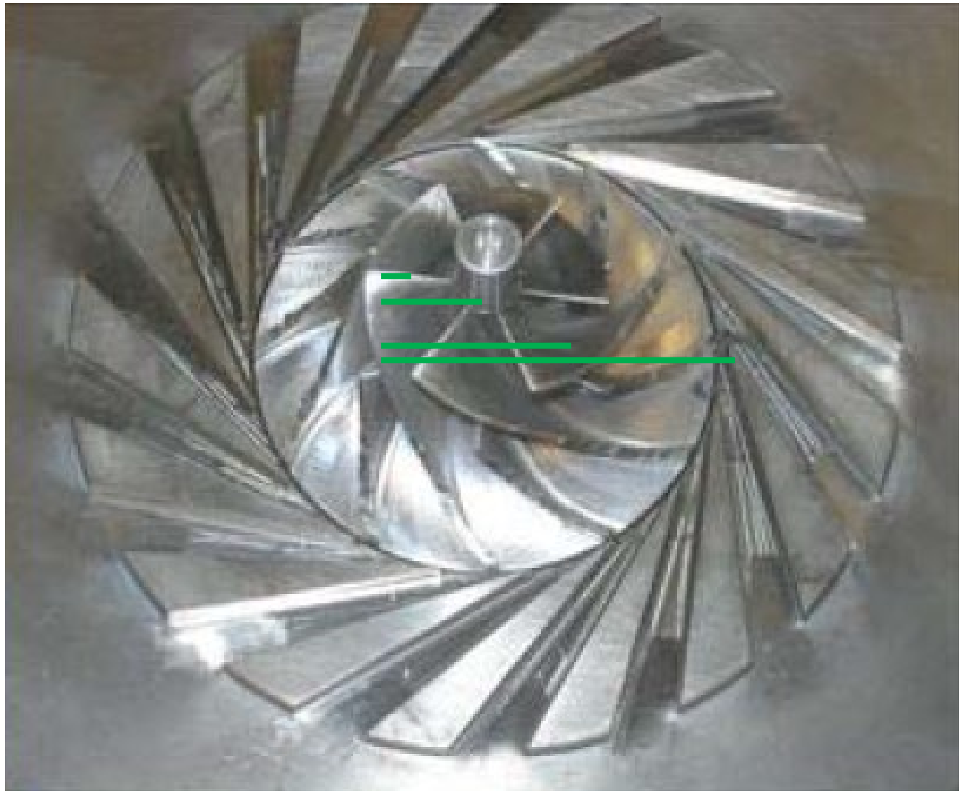
SNL compressor wheel, from Wright et al. (2010)

Model verification

Specification	Units	Value
Known, from Wright et al. (2010)		
Number of full blades	-	6
Number of splitter blades	-	6
Number of vaned diffuser channels	-	17
Blade angle at impeller inlet	°	50.0
Blade angle at impeller exit (backswept)	°	50.0
Vaned diffuser angle at diffuser inlet	°	71.5
Hub radius	mm	2.54
Shroud radius	mm	9.37
Impeller exit radius	mm	18.68
Tip clearance	mm	0.254
Blade thickness	mm	0.76
Blade height at exit	mm	1.71
Nominal mass flow rate	kg/s	3.53
Total pressure at inlet	kPa	7687
Total temperature at inlet	°C	32.15
Assumed		
Ratio of splitter blade to full blade meridional length	-	0.5
Blade angle at impeller inlet (at hub, mean position and shroud)	°	50.0
Vaned diffuser inlet diameter	mm	40
Vaned diffuser exit diameter	mm	75
Vaned diffuser height	mm	1.71
Collector exit diameter	mm	29.89

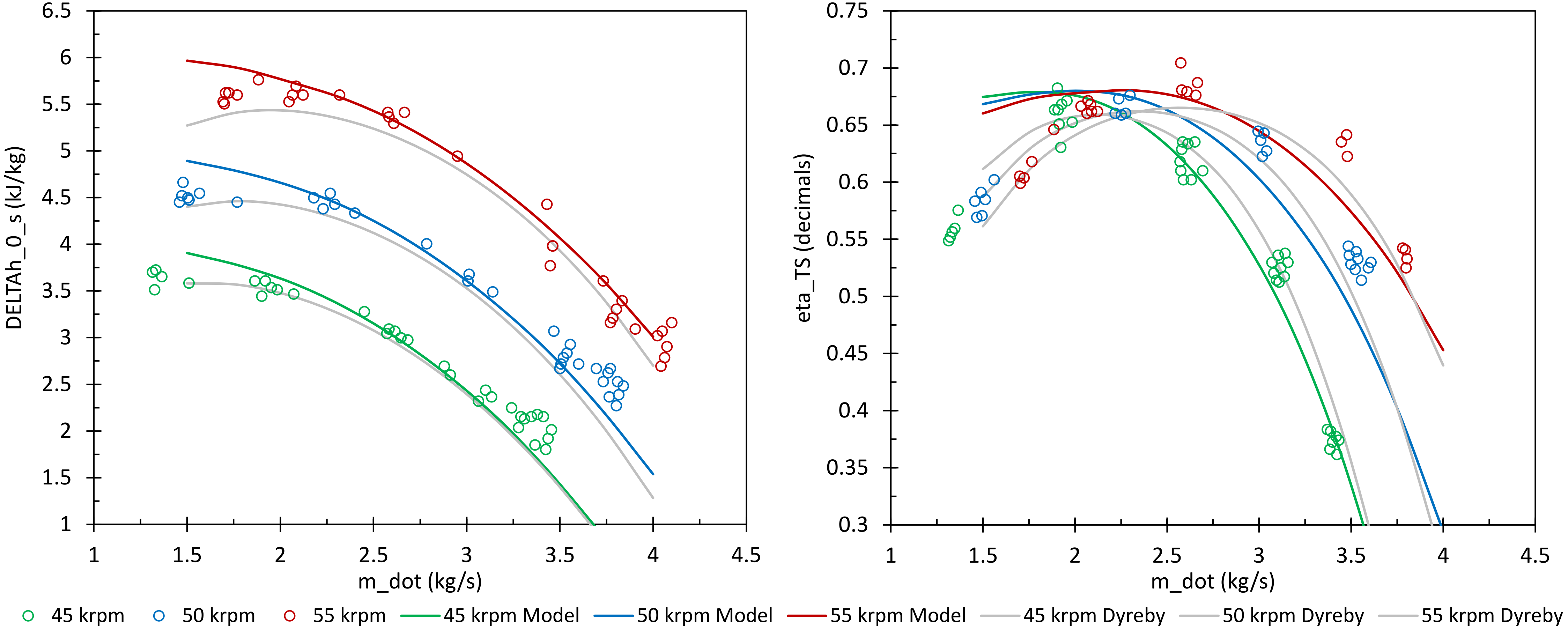
Model verification





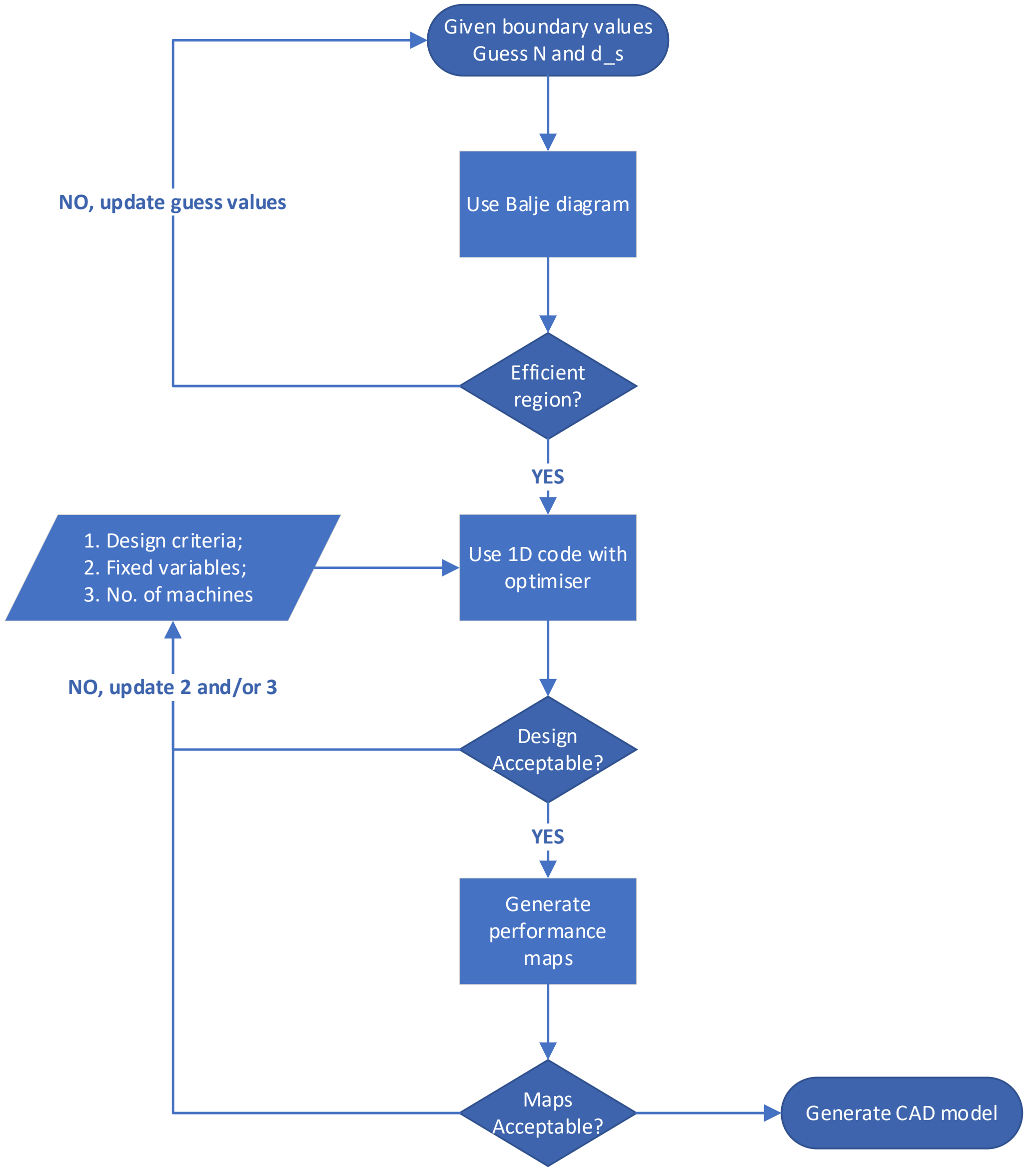
Images of SNL compressor, from Wright et al. (2010)

Model verification

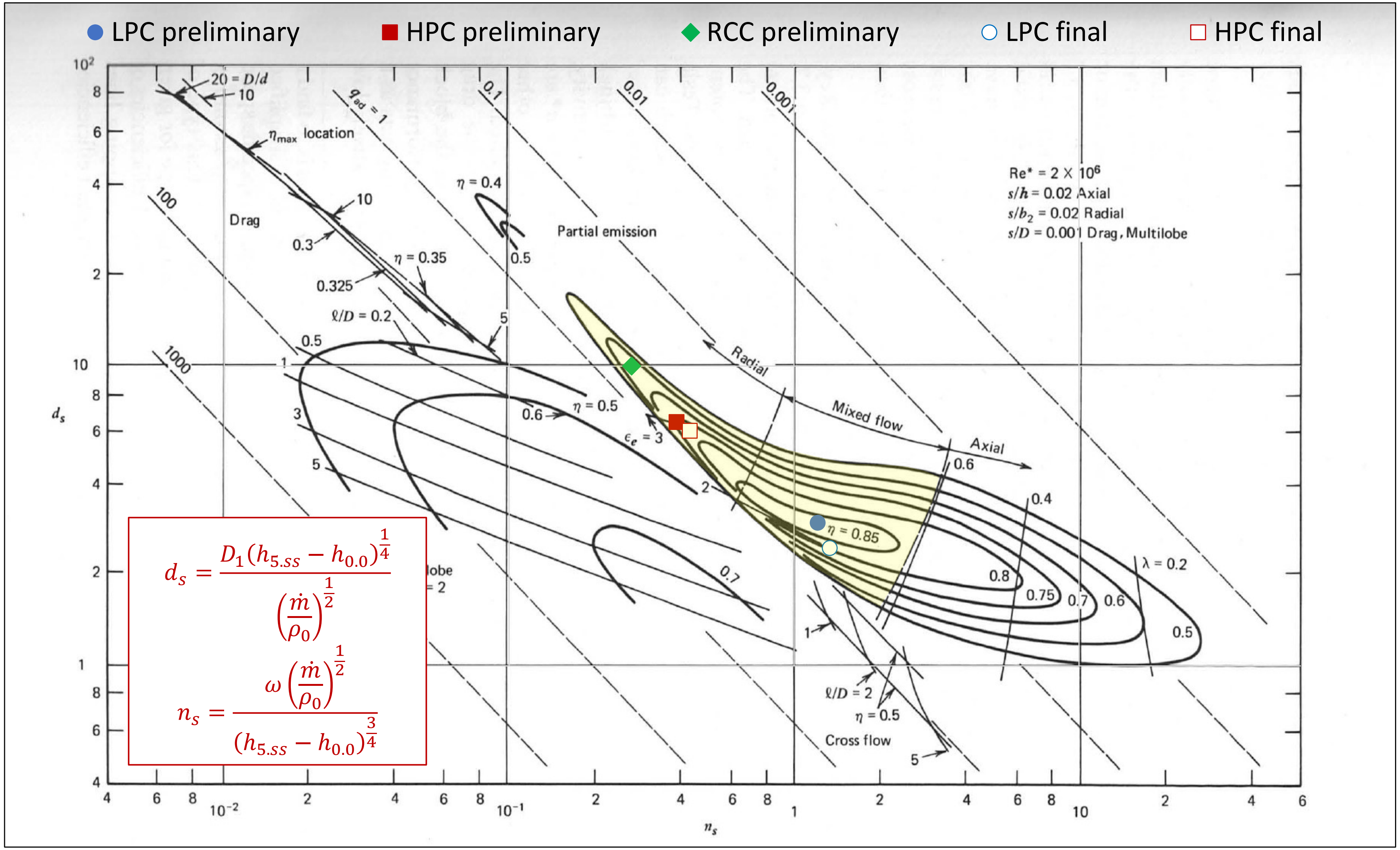


Verification results, test data from Wright et al. (2010)

Sizing method



Initial sizing



$$d_s = \frac{D_1 (h_{5.ss} - h_{0.0})^{\frac{1}{4}}}{\left(\frac{\dot{m}}{\rho_0}\right)^{\frac{1}{2}}}$$

$$n_s = \frac{\omega \left(\frac{\dot{m}}{\rho_0}\right)^{\frac{1}{2}}}{(h_{5.ss} - h_{0.0})^{\frac{3}{4}}}$$

Marked up specific diameter-speed diagram, original image from Balje (1981)

1D model inputs

Specification	Units	LPC	HPC
Design criteria			
Mass flow rate	kg/s	397	397
Total pressure at inlet	kPa	7353	9768
Total temperature at inlet	°C	45	45
Total pressure ratio	-	1.356	2.560
Total-to-total efficiency (target)	%	89	89
Fixed variables			
Number of full blades	-	19	19
Number of vaned diffuser channels	-	28	28
Nominal design speed	rpm	9000	9000
Optimised variables			
Hub to shroud radius ratio	-	[0.3, 0.6]	
Shroud to tip radius ratio	-	[0.35, 0.65]	
Vaned diffuser inlet to impeller exit radius ratio	-	[1.025, 1.075]	
Vaned diffuser exit to inlet radius ratio	-	[1.25, 1.75]	
Inlet swirl angle	°	[0, 35]	
Blade angle at impeller inlet (mean position)	°	[25, 50]	
Blade angle at impeller exit (backswept)	°	[25, 50]	

$$OBJECTIVE = X_1\left(\left|\frac{\eta_{TT} - \eta_{TT.target}}{\eta_{TT.target}}\right|\right) + X_2\left(\left|\frac{\eta_{TS} - \eta_{TT.target}}{\eta_{TT.target}}\right|\right)$$

$$X_1 = 0.9; X_2 = 0.1$$

1D model results

Specification	Units	LPC	HPC
Calculated geometry			
Inlet swirl angle	°	35	17.5
Blade angle at impeller inlet (at hub, mean position and shroud)	°	25.5	37.5
Blade angle at impeller exit (backswept)	°	49.5	37.5
Vaned diffuser mean flow path angle	°	60.5	68.5
Blade height at exit; vaned diffuser height	mm	29.280	8.334
Inlet guide vane upstream diameter	mm	200.7	137.0
Hub diameter	mm	70.0	70.5
Shroud diameter	mm	232.6	157.6
Impeller exit diameter	mm	358.0	450.2
Vaned diffuser inlet diameter	mm	384.9	483.9
Vaned diffuser exit diameter	mm	672.6	846.8
Volute exit diameter	mm	211.3	105.5
Axial length	mm	115.80	91.33
Inertia	kg-mm^2	78 968	181 881
Performance at design point			
Minimum flow coefficient	-	0.0382	0.0084
Maximum flow coefficient	-	0.1339	0.0314
Volume flow rate at inlet	m^3/s	2.062	0.8986
Isentropic head	kJ/kg	11.61	27.30
Total-to-total efficiency (actual)	%	88.79	89.07
Total-to-static efficiency	%	80.59	80.19
Compressor power	MW	-5.193	-12.166

Performance maps

Pressure (kPa)	Temperature (degC)	Mass Flow (kg/s)	PR	eta_TT	CM	CS	DELTAh_0_s (kJ/kg)	eta_TT	Q_dot_in (m3/s)	Speed (rpm)
6549.01	38.65	483.80	1.15	0.62	130.40	504.60	5.69	0.64	2.86	9000
7381.07	52.71	556.27	1.05	0.27	136.00	504.60	1.24	0.19	3.23	9000
6649.79	45.57	411.97	1.22	0.78	110.60	504.60	8.05	0.78	2.57	9000
6820.67	49.59	358.89	1.28	0.86	94.52	504.60	10.37	0.86	2.23	9000
8142.50	49.29	541.28	1.29	0.83	119.40	504.60	9.18	0.83	2.44	9000
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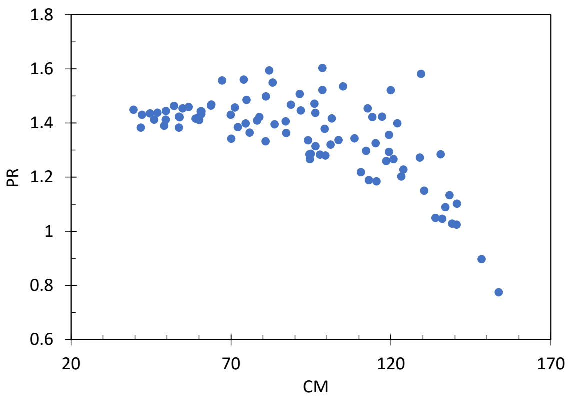
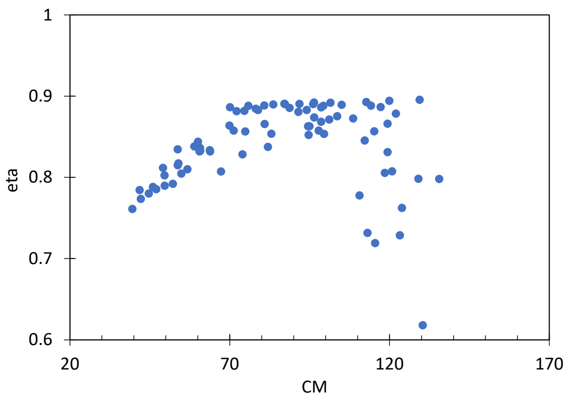
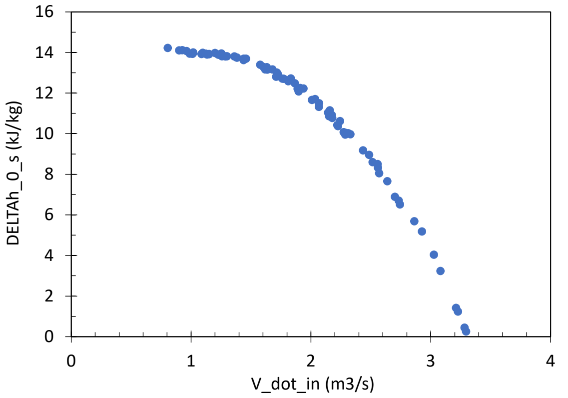
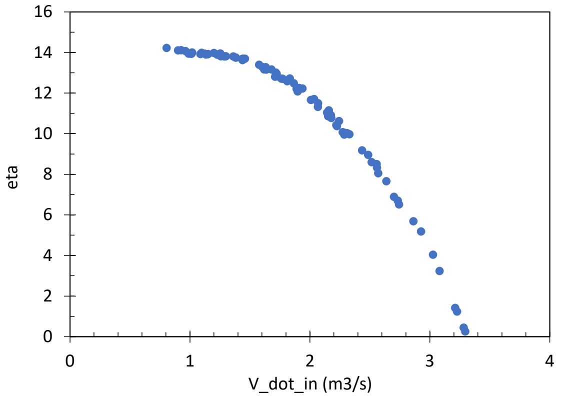
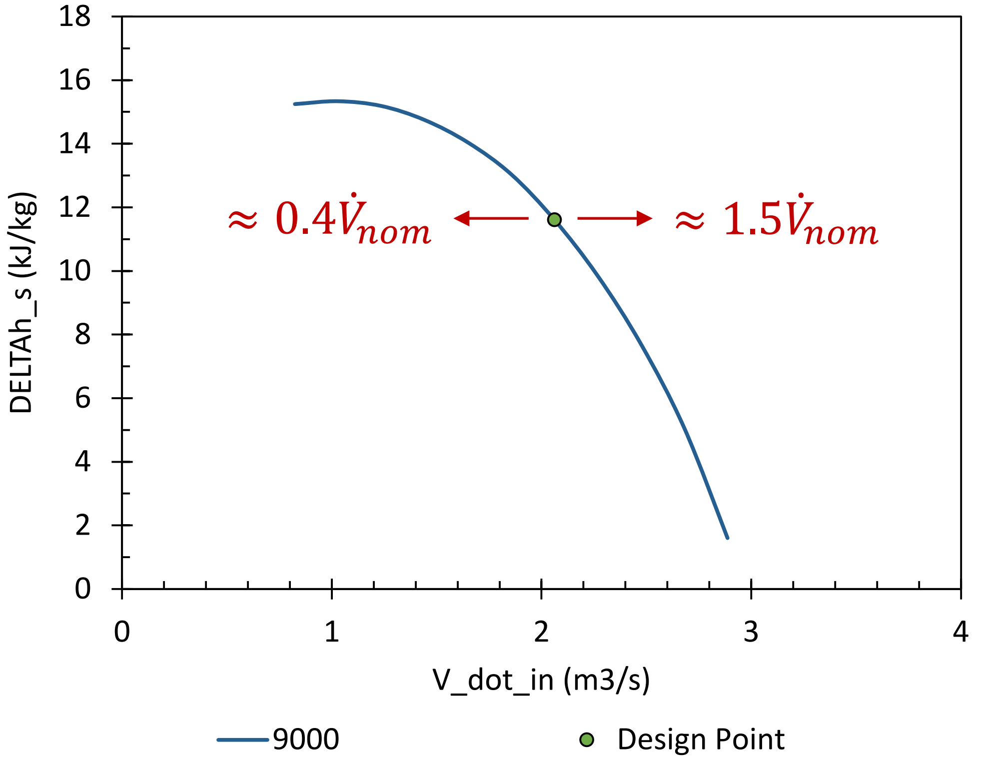


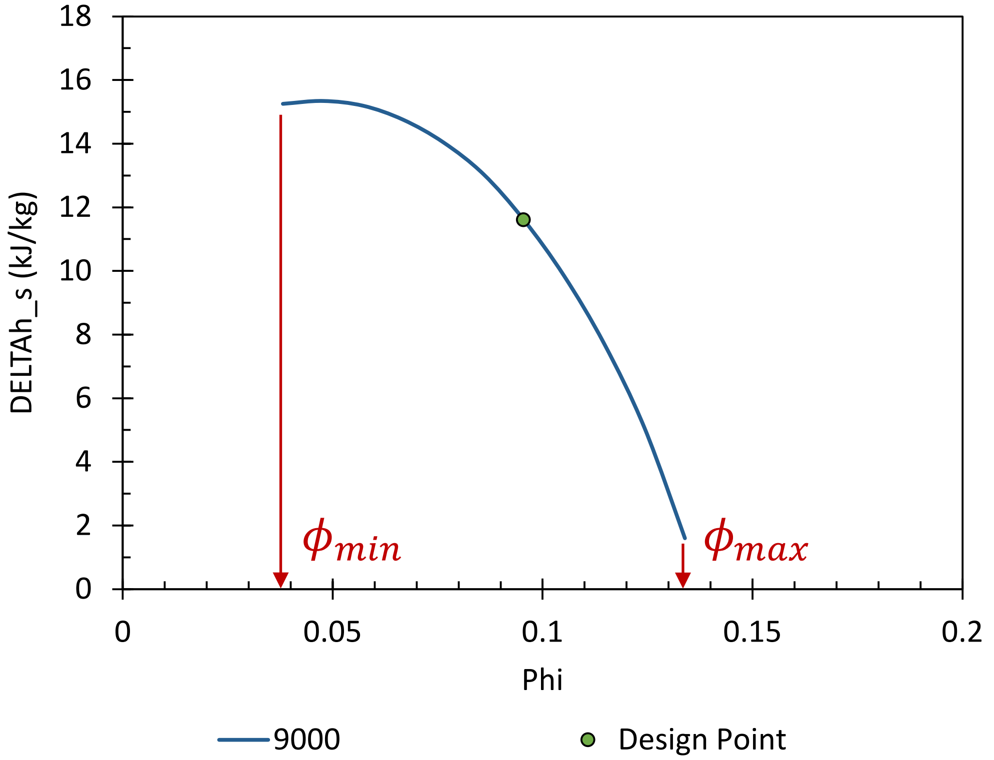






Performance maps





Performance maps

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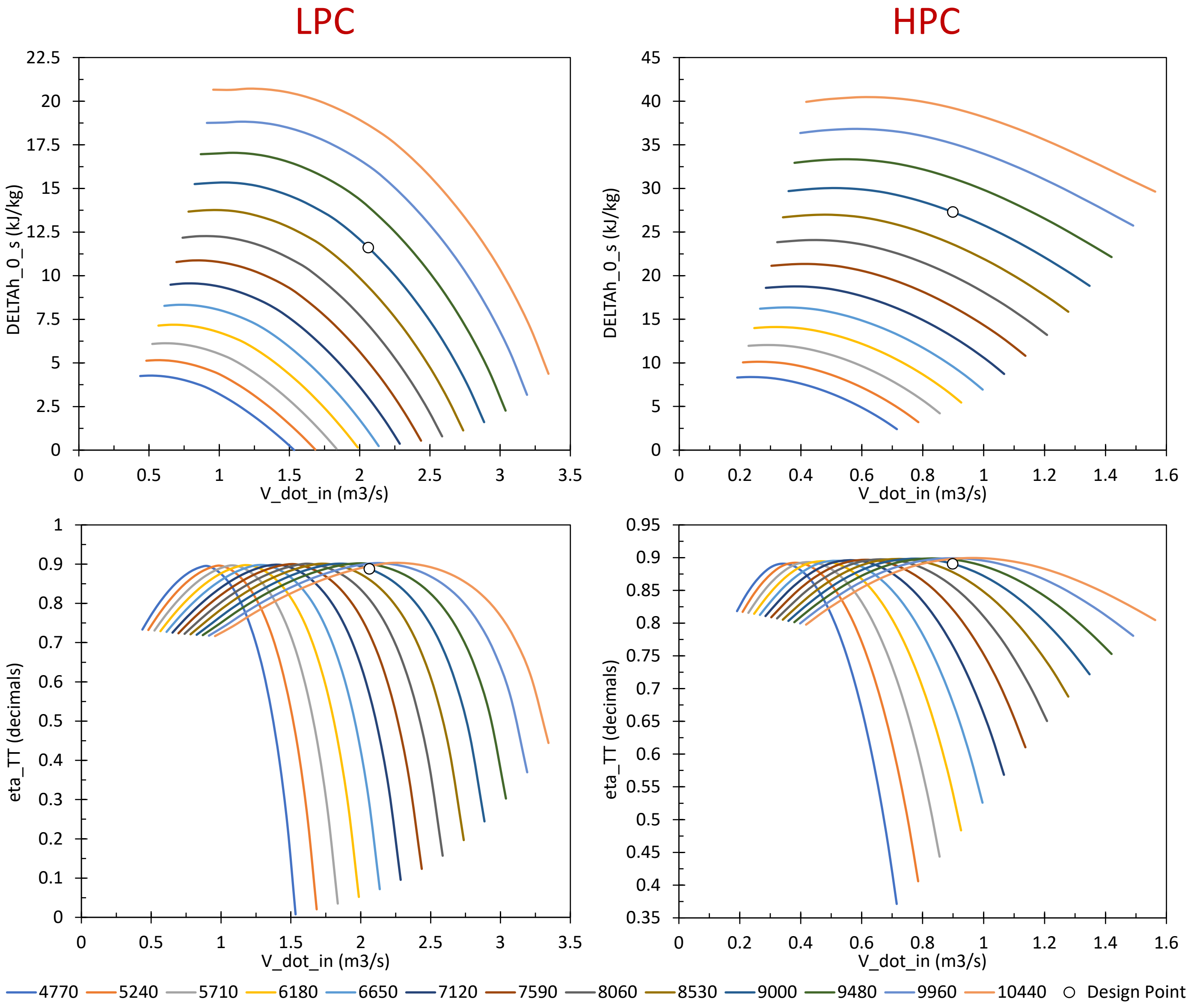
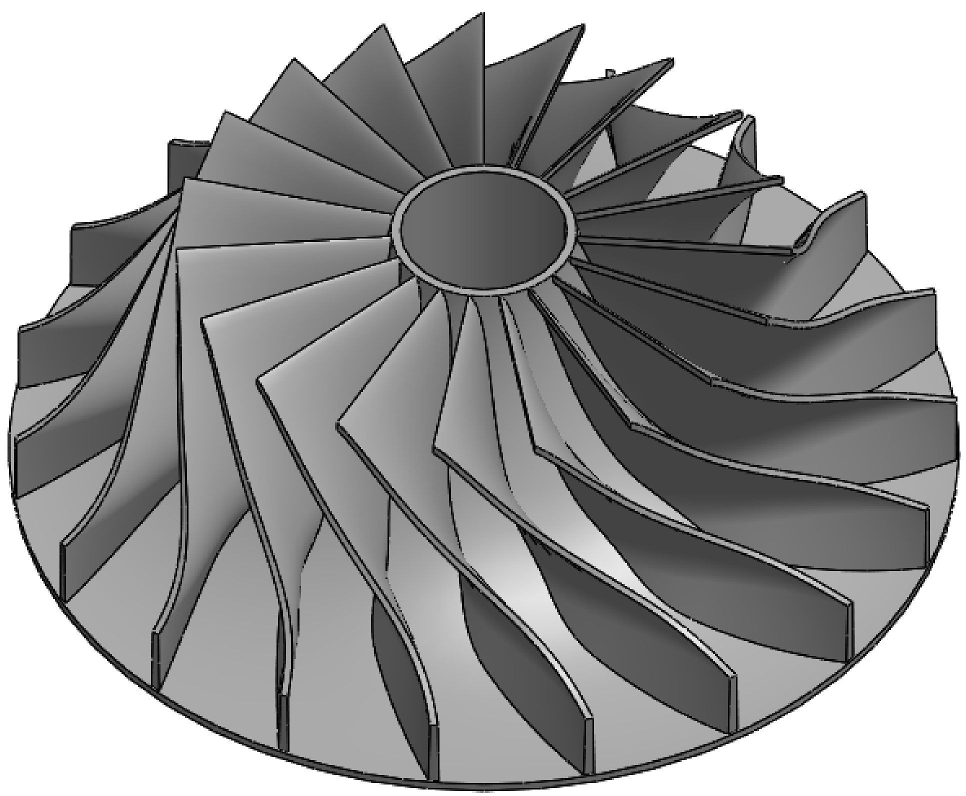


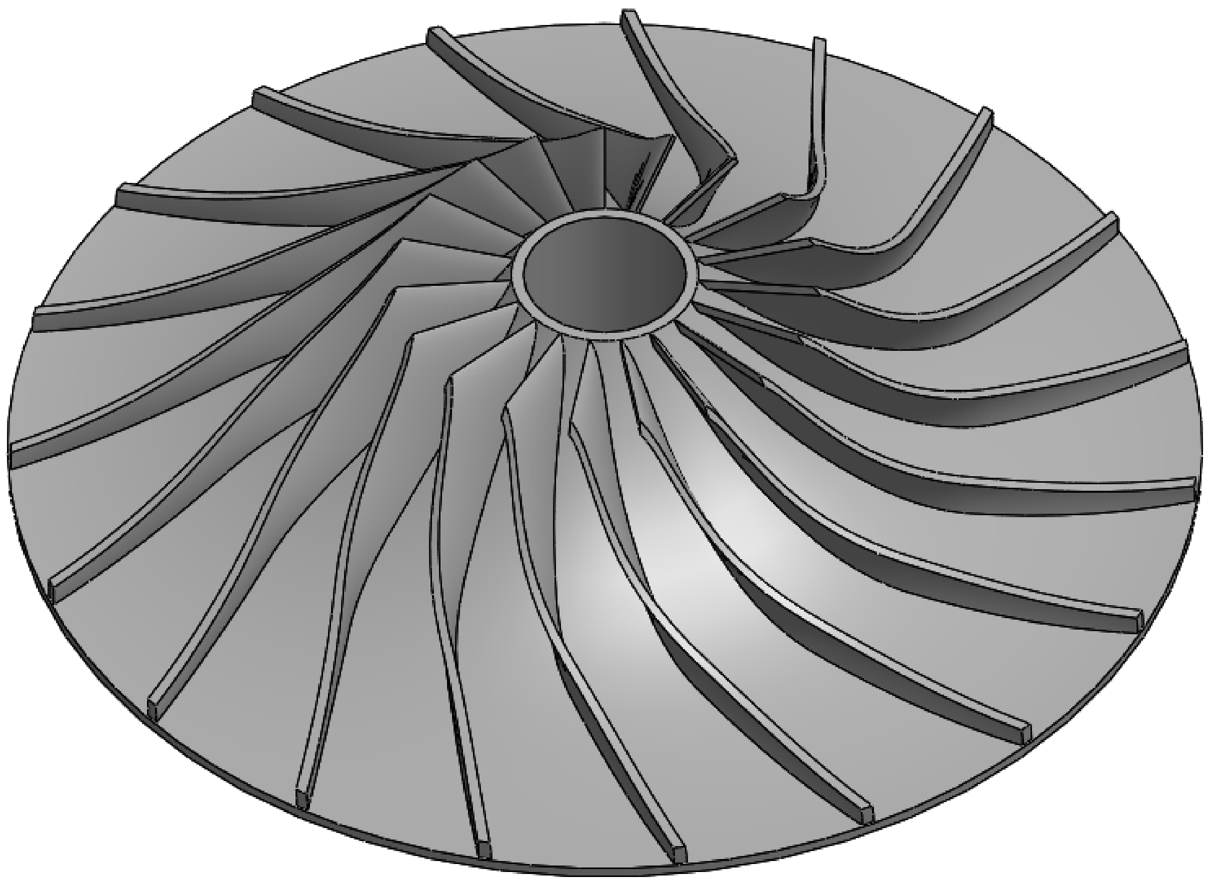
CAD models

LPC



358 x 116

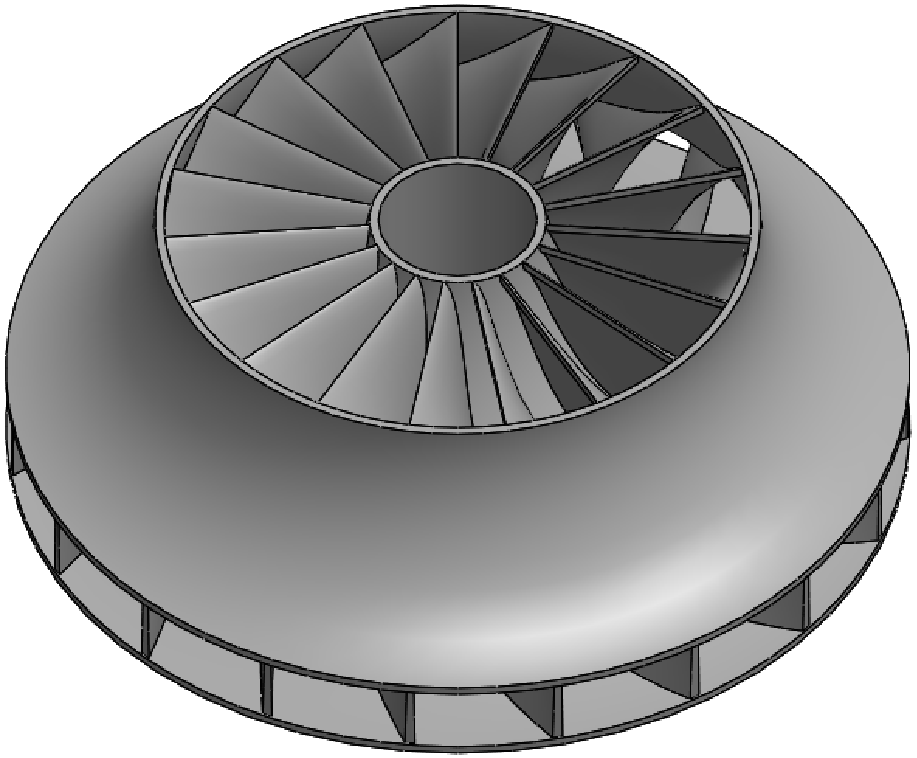
HPC



450 x 91

CAD models

LPC



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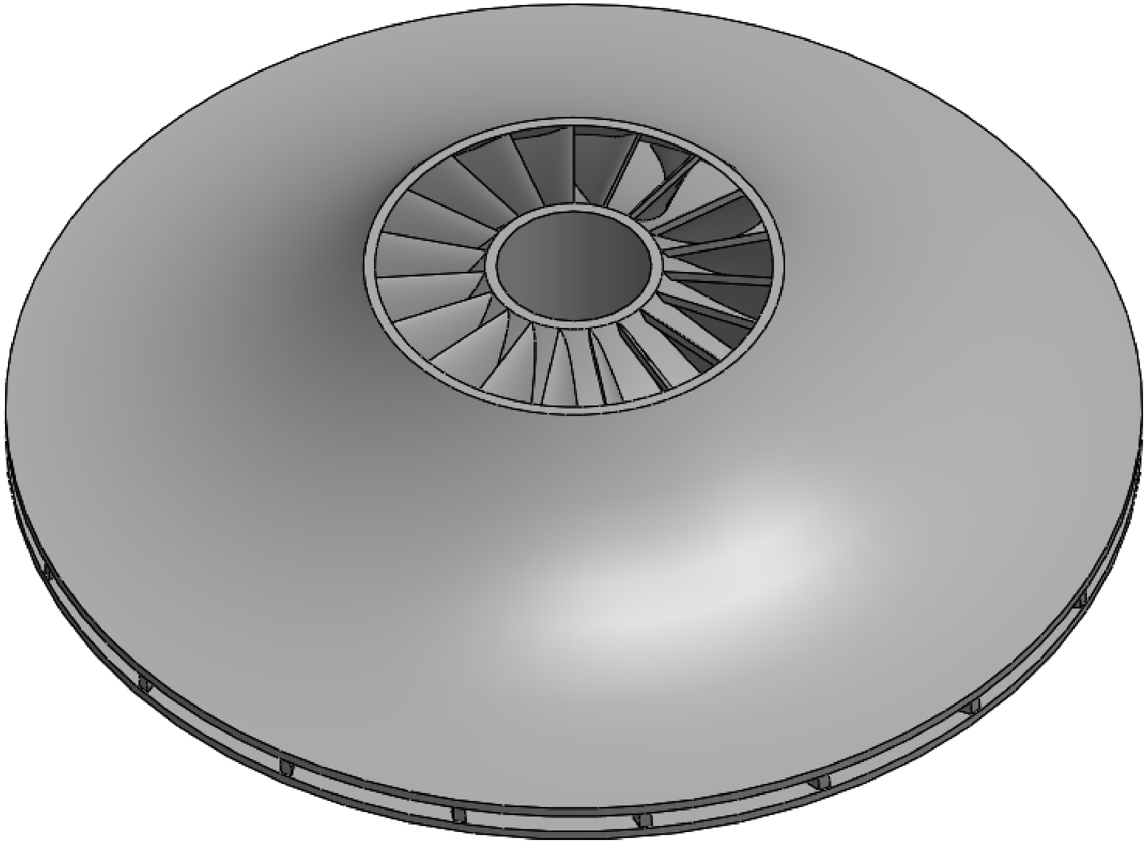
HPC



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Minimum static temperatures

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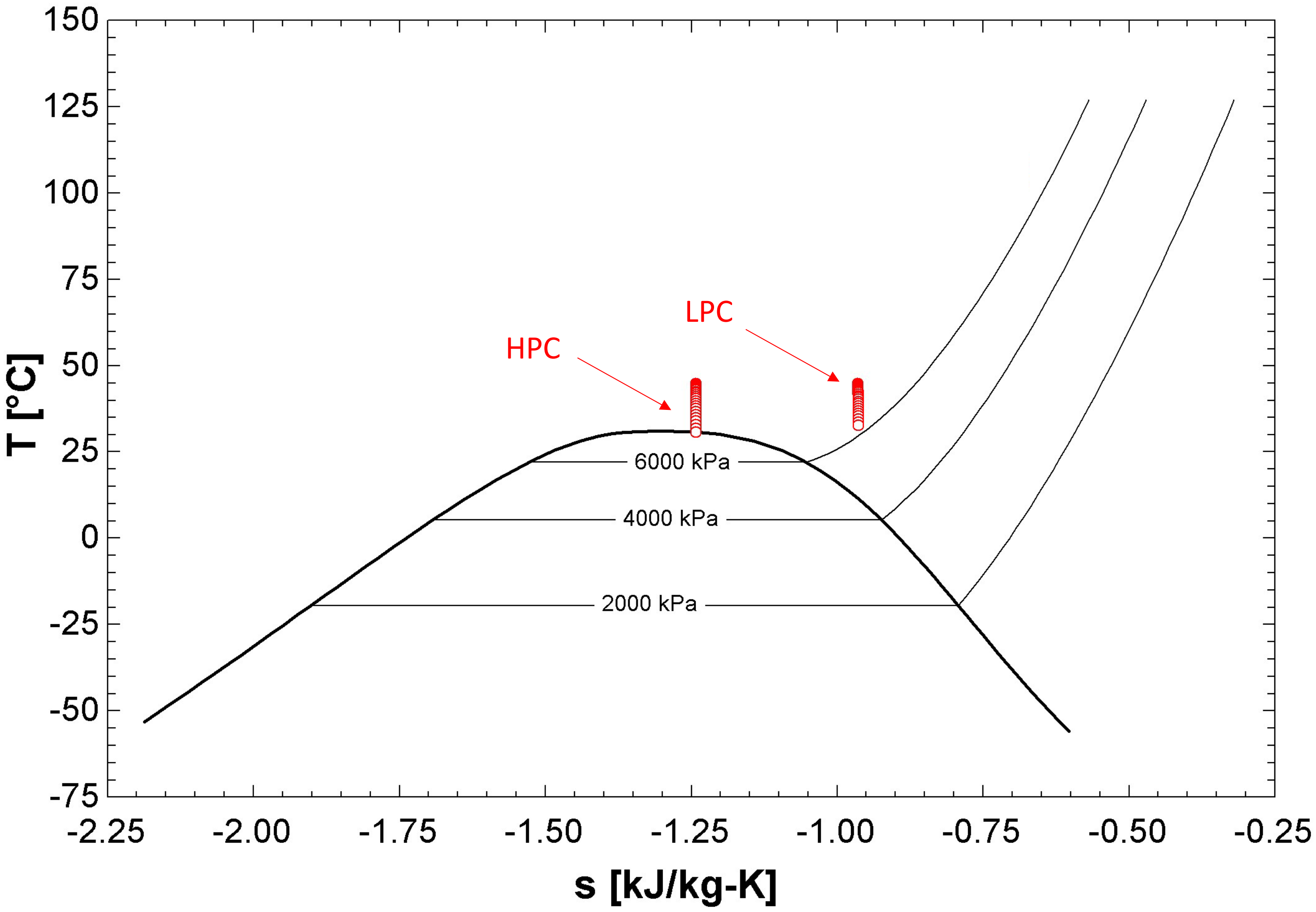
For the HPC, when operating at the highest speed and flow rate, a two-phase flow state may be encountered.



Summary and conclusions

- Dynamic compressor models are required for transient simulation studies of sCO_2 cycles.
- Most researchers apply Dyreby's correlations, which is useful, but has shortcomings.
- Except for KAIST-TMD and AlFa CCD, which are not fully documented and leave room for improvement, there are no suitable tools available to size and develop performance maps for sCO_2 radial compressors.

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  - A 1D mean-line code to size centrifugal compressors was developed and verified.
  - The code was used to size centrifugal compressors and develop performance maps.
  - 3D models were developed to estimate the inertia of the compressors.

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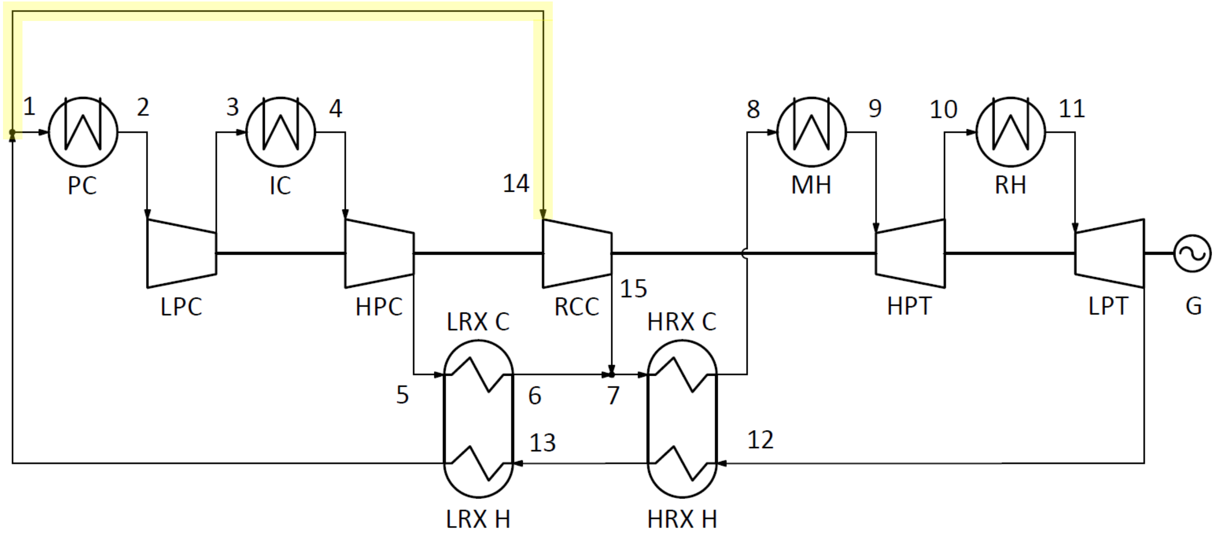
- The maps and inertia values may be used to model compressors in simulation software.
- The methods employed in this work may be used by others to model centrifugal compressors.

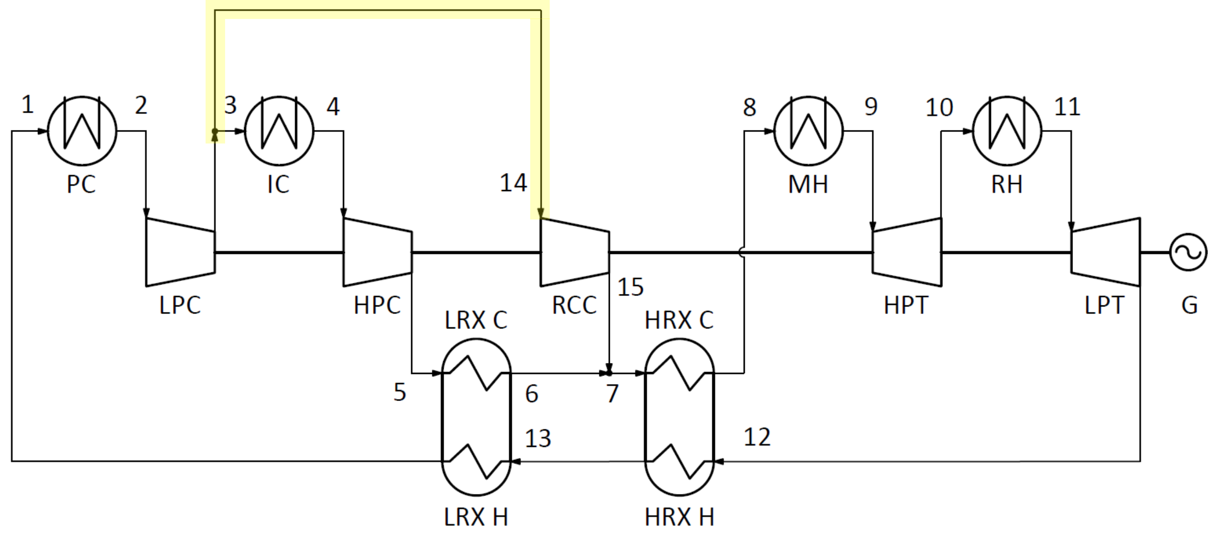
Q&A

Cycles of interest

Partial cooling with reheating cycle



Recompression with intercooling and reheating cycle



PC: Pre-cooler

IC: Intercooler

LPC: Low pressure compressor

HPC: High pressure compressor

RCC: Recompression compressor

MH: Main heater

RH: Reheater

HPT: High pressure turbine

LPT: Low pressure turbine

LRX: Low temperature recuperator

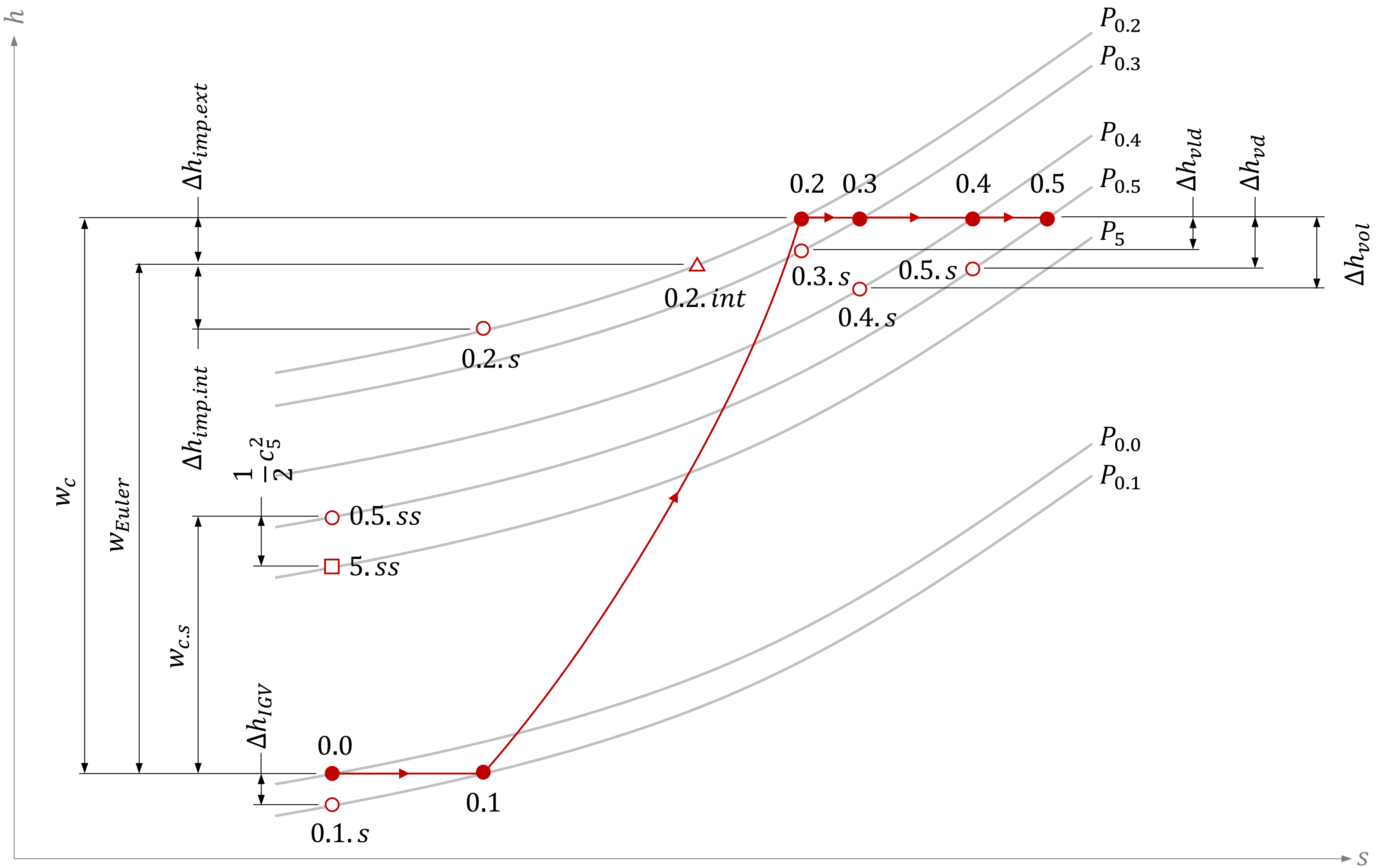
HRX: High temperature recuperator

_C: Cold side

_H: Hot side

G: Generator

Mollier diagram



Governing equations

Mass Balance (all elements)

$$\dot{m} = \rho A c$$

Energy Balance (impeller)

$$h_{0.out.s} = h_{0.in} - w_{Euler} - \Delta h_{imp.int}$$

$$h_{0.out} = h_{0.in} - w_{Euler} + \Delta h_{imp.ext}$$

Energy Balance (other elements)

$$h_{0.out.s} = h_{0.in} - \Delta h_{element}$$

$$h_{0.out} = h_{0.in}$$

Entropy Balance (all elements)

$$s_{in} = f(P_{in}, T_{in})$$

$$s_{out.s} = s_{in}$$

$$P_{0.out} = f(h_{0.out.s}, s_{out.s})$$

$$T_{0.out} = f(h_{0.out}, P_{0.out})$$

Governing equations

Real gas fluid property relationships

$$h_0 = h + \frac{1}{2}c^2$$

$$h, \rho, \nu, ss = f(P, T)$$

Work and efficiency definitions

$$w_{c.s} = h_{0.0} - h_{0.5.ss}$$

$$w_c = h_{0.0} - h_{0.5}$$

$$\eta_{TS} = \frac{h_{0.0} - h_{5.ss}}{w_c}$$

$$\eta_{TT} = \frac{w_{c.s}}{w_c}$$

Correlations

Group	Loss/ Model	Source
	Inlet guide vanes	(Galvas, 1973)
Internal losses	Skin friction	Jansen (as cited by Ameli et al., 2018; Harrison, 2020)
Internal losses	Impeller blade loading	(Aungier, 1995)
Internal losses	Hub to shroud (for shrouded impellers)	(Aungier, 1995)
Internal losses	Mixing	(Aungier, 1995)
Internal losses	Clearance (for unshrouded impellers)	Jansen (as cited by Zhang et al., 2019)
Internal losses	Incidence	(Aungier, 2000)
Internal losses	Entrance diffusion	(Aungier, 1995)
Internal losses	Choke	(Aungier, 1995)
Internal losses	Shock	(Aungier, 1995)
External losses	Disk friction	Daily & Nece (as cited by Zhang et al., 2019)
External losses	Recirculation	Coppage & Dallenbach (as cited by Zhang et al., 2019)
External losses	Leakage (for unshrouded impellers)	(Aungier, 1995)
	Vaneless space (friction)	Based on Jansen (as cited by Ameli et al., 2018)
	Vaned diffuser (incidence)	Aungier (as cited by Zhang et al., 2019)
	Vaned diffuser (friction)	Based on Jansen (as cited by Ameli et al., 2018)
	Volute pressure recovery	Japikse & Baines (1997)
	Slip factor	Wiesner (1967)

Software

EES

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python™

SolarPILOT

Related work

- Steady state cycle study:
  - du Sart, C.F., Rousseau, P. & Laubscher, R. 2024. Comparing the partial cooling and recompression cycles for a 50 MWe sCO2 CSP plant using detailed recuperator models. Renewable Energy. DOI: 10.1016/j.renene.2024.119980.

- Solar field and receiver studies:
  - Heydenrych, J.M., Rousseau, P.G. & du Sart, C.F. 2022. Reduced-order modelling of central solar tower receivers using an equivalent thermal resistance network. In Proceedings of the 16th international conference on heat transfer, fluid mechanics and thermodynamics (HEFAT-16). Virtual: HEFAT. 911–916. Available: https://www.researchgate.net/publication/363173202.
  - Heydenrych, J.M., Rousseau, P.G. & du Sart, C.F. 2023. A reduced order modelling methodology for concentrated solar power external cylindrical receivers. In Proceedings of the 17th international heat transfer conference (IHTC-17). Cape Town: Begell House. Available: https://ihtcdigitallibrary.com/conferences/ihtc17,7188217e24389634,15e3d1eb26dcb54a.html.

- Heat rejection system study:
  - Abrahams, L., du Sart, C. & Laubscher, R. 2022. Design of an air-cooled heat rejection system for a SCO2 concentrated solar power plant. In 16th international conference on heat transfer, fluid mechanics and thermodynamics (HEFAT-16). Virtual: HEFAT. 288–293. Available: https://www.researchgate.net/publication/363173234.

- Turbine studies:
  - du Sart, C.F., Rousseau, P. & Laubscher, R. 2024. A method to develop centrifugal turbine performance maps for off-design and dynamic simulation studies of sCO2 cycles. In Review.
  - Laubscher, R., Rousseau, P., Van Der Spuy, J., du Sart, C. & Johannes, P. A unified thermofluid network simulation methodology to model centrifugal compressors with supercritical real gas working fluids. In Review.

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